Effect of Auditory Peripheral Displays On Unmanned Aerial Vehicle Operator Performance

by

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14. ABSTRACT
With advanced autonomy, Unmanned Aerial Vehicle (UAV) operations will likely be conducted by single operators controlling multiple UAVs. As operator attention is divided across multiple supervisory tasks, there is a need to support the operator?s awareness of the state of the tasks for safe and effective task management. This research explores enhancing audio cues of UAV interfaces for this futuristic control of multiple UAVs by a single operator. This thesis specifically assesses the value of continuous and discrete audio cues as indicators of course‐deviations or late‐arrivals to targets for UAV missions with single and multiple UAVs. In particular, this thesis addresses two questions: (1) when compared with discrete audio, does continuous audio better aid human supervision of UAV operations, and (2) is the effectiveness of the discrete or continuous audio support dependent on operator workload? An experiment was carried out on the Multiple Autonomous Unmanned Vehicle Experiment (MAUVE) test bed with 44 military participants. Specifically, two continuous audio alerts were mapped to two human supervisory tasks within MAUVE. These continuous alerts were tested against single beep discrete alerts. The results show that the use of the continuous audio alerts enhances a single operator?s performance in monitoring single and multiple, semi‐autonomous vehicles. The results also emphasize the necessity to properly integrate the continuous audio with other auditory alarms and visual representations in a display, as it is possible for discrete audio alerts to be masked by continuous audio, leaving operators reliant on the visual aspects of the display.

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An experiment was carried out on the Multiple Autonomous Unmanned Vehicle Experiment (MAUVE) test bed with 44 military participants. Specifically, two continuous audio alerts were mapped to two human supervisory tasks within MAUVE. These continuous alerts were tested against single beep discrete alerts. The results show that the use of the continuous audio alerts enhances a single operator's performance in monitoring single and multiple, semi-autonomous vehicles. The results also emphasize the necessity to properly integrate the continuous audio with other auditory alarms and visual representations in a display, as it is possible for discrete audio alerts to be masked by continuous audio, leaving operators reliant on the visual aspects of the display.

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Nomenclature

ANOVA	Analysis of Variance
COCOM	Combatant Commander
DOD	Department of Defense
DSV	Decision Support Visualization
HDiSP	Headset Display
MALE	Minimum Altitude, Long Endurance
MAUVE	Multiple Aerial Unmanned Vehicle Experiment
MIT	Massachusetts Institute of Technology
MMWS	Multi-Modal Workstation
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
RTB	Return to Base
TLX	Task Load Index
TOT	Time on Target
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VTUAV	Vertical-take-off-and-landing Tactical Unmanned Aerial Vehicle
3D	Three-dimensional

1. Introduction

The use of Unmanned Aerial Vehicles (UAVs) is growing in the military, federal, and civil domains. Worldwide, in the next 8 years UAVs will be a 15.7 billion dollar industry, where in the United States alone the plan is to have 9,420 mini UAVs, 775 tactical UAVs, 570 minimum altitude, long endurance (MALE) UAVs and 60 Global Hawks (Tsach, Peled, Penn, Keshales, & Guedj, 2007). In fall 2006, over 40 countries were operating UAVs and 80 types of UAVs were in existence, with the United States operating 3,000 UAVs and the North Atlantic Treaty Organization (NATO) operating 3,600 UAVs (Culbertson, 2006). UAVs are not just in demand on the battlefield; other government departments seeking the use of UAVs include the Department of Homeland Security and the U.S. Coast Guard for law enforcement and border patrol (DOD, 2007). UAVs are also sought after in support of humanitarian relief efforts, such as with flood regions in the United States. In Missouri in May 2007, Air Force Predator UAVs were on standby to offer assistance in the flooding recovery efforts (Arana-Barradas, 2007).

In his spring 2008 speech to Air Force officers at Air University, Defense Secretary Robert M. Gates pointed to the fact that within the Department of Defense (DOD) there has been a 25-fold increase in UAV operations since 2001. He then went on to say that this increase is not enough. To support the troops in Afghanistan and Iraq, work must be done to further integrate UAVs into the force and operations (Gates, 2008).

One of the efforts to further integrate UAVs into the force is to maximize the human-to-UAV ratio as a "force multiplier." In fall 2006, General William T. Hobbins, in command of the Allied Air Component Command and European Command Air Component, publicly stated that part of the solution to the growing UAV demand will be to have a single operator controlling multiple UAVs (Culbertson, 2006), because a

single operator is more efficient for cost and operational tempo (Barbato, Feitshans, Williams, & Hughes, 2003; Tsach et al., 2007).

To achieve force multiplication, humans will need to perform a supervisory role as vehicles become more autonomous, instead of attending to low-level tasks like manually flying the aircraft. One way to help humans efficiently and safely execute this supervisory task is to maximize the use of each sensory channel to convey information. In aviation, pilots use visual and auditory senses when flying an aircraft. A unique aspect of UAV supervision, which occurs remotely, is that if the operator requires natural signals that occur in manned aviation, the signals must be synthetically created. UAV displays are predominantly visual displays and are typically mounted in mobile trailers, truck beds, or backpacks. With advancing technology, there are new, unexplored ways to provide display information across multiple sensory channels.

When there is an overload of information, utilizing different and multiple sensory channels can effectively increase the amount of information processed (Wickens, Lee, Liu, & Becker, 2004). When using multiple sensory channels (or modes), certain forms of information are better conveyed through an audio presentation, while others are better conveyed through a visual presentation (Deatherage, 1972; Sorkin, 1987). Table 1-1 provides a list of known benefits for the visual and audio channel presentations. A notable benefit for auditory presentation is its effectiveness at representing simple events occurring in time and requiring immediate action, as opposed to complex events occurring at a location in space and not requiring immediate action. Further, because of its omnipresence, audio is usually the preferred sense for presenting a warning (Simpson & Williams, 1980; Sorkin, 1987). Thus, the audio channel is effective in warning of potential problems.

Table 1-1: Auditory Versus Visual Presentations (Deatherage, 1972; Sorkin, 1987).

Use auditory presentation if:	*Use visual presentation if:*
1. The message is simple.	1. The message is complex.
2. The message is short.	2. The message is long.
3. The message will not be referred to later.	3. The message will be referred to later.
4. The message deals with events in time.	4. The message deals with location in space.
5. The message calls for immediate action.	5. The message does not call for immediate action.
6. The visual system of the person is overburdened.	6. The auditory system of the person is overburdened.
7. The receiving location is too bright or dark.	7. The receiving location is too noisy.
8. The person's job requires him to move about continually.	8. The person's job allows him to remain in one position.

In addition to information presentation modality, another concern is what specific information is conveyed. When placed in a supervisory control role, a human operator may have to respond to an interruption to a primary task of monitoring. To respond, the operator needs an understanding of what has occurred in the system, either as an output of an action or as a result of an unseen change (Scott, Mercier, Cummings, & Wang, 2006; St.John, Smallman, & Manes, 2005). A potential way to support operator understanding of a monitored task's state is to continuously present information so that the operator can immediately determine a task's current state, as well as projected future states.

The objective of this research is to explore ways to combine audio displays with visual displays to support supervisory tasks. In particular, this research focuses on comparing continuous to discrete audio displays to understand the effects of a constant versus discrete presentation of information. Discrete audio displays play an alert once for about a second when a monitored task exceeds limits. In contrast, continuous audio displays are audio displays that always indicate some system state. Chapter 2, *Background*, will further frame the context of the research of this thesis.

1.1. Problem Statement

The primary questions addressed through this research are:

1. When compared with discrete audio, does continuous audio better aid human supervision of UAV operations?
2. Is the effectiveness of the discrete or continuous audio support dependent on operator workload?

Three steps are followed in this thesis to address the research questions: (1) a multiple-UAV simulator, the Multiple Aerial Unmanned Vehicle Experiment (MAUVE) test bed, is selected, (2) audio displays are developed and integrated into this multiple-UAV simulator, and (3) human operator performance is tested in the MAUVE environment to compare continuous and discrete audio displays.

1.2. Thesis Organization

This thesis is organized into seven chapters:

- Chapter 1, *Introduction*, provides the motivation of this research, research questions, and the research objectives of this thesis.
- Chapter 2, *Background*, reviews the current Unmanned Aerial System (UAS) environment and the needs of the human operator supervising UAS operations. The chapter then frames the research of this thesis in terms of meeting the needs of human operators supervising UAS operations.
- Chapter 3, *Simulator and Interface Design*, presents details of MAUVE and the associated tasks operators supervise on MAUVE. The chapter then defines the four audio alerts tested in this experiment with a technical description of the alerts and their functions.

- Chapter 4, *Method*, presents the research questions of the experiment, the experimental apparatus, the experimental task, the participants, the independent and dependent variables, and the data collection.
- Chapter 5, *Results*, discusses the statistical analysis results. The chapter also provides a description of the participants' post-test subjective feedback.
- Chapter 6, *Discussion*, synthesizes the applicable lessons that can be extrapolated from the experimental results.
- Chapter 7, *Conclusion*, reviews the answers to the research questions, discusses continuous audio integration in the real world, and suggests areas for future research.

2. Background

This chapter highlights the current shift toward unmanned systems and the needs this shift generates for controlling these unmanned systems. It presents attention theories linked to possible solutions for aiding human operators in supervising unmanned systems. Further, this continuous audio research is framed in the context of previous research in audio display support of supervisory tasks. Finally, a discussion of the research hypotheses and the groundings of these hypotheses closes the chapter.

2.1. UAS Evolution

2.1.1. The Current Push

Senior military officials see the need for integrating more UAV operations in support of the troops on the ground in Iraq and Afghanistan (USAF, 2007; Whitney, 2007). Four star Combatant Commanders (COCOMs) highly desire unmanned systems for the many roles these systems can play (Sullivan, 2008; DOD, 2007). Major advantages of unmanned systems are that they are cheaper and have more endurance than manned aircraft (Barbato et al., 2003; Gates, 2008). Many of the integral roles that COCOMs may envision for UAVs are encapsulated in recent work by Nehme, Crandall, and Cummings (2007), which includes a taxonomy of all the current and potential roles that UAVs can perform with today's technology (Figure 2-1).

Unmanned vehicles are changing how warfighting is conducted, and they are vital to providing intelligence and reconnaissance for troops on the ground. As of October 2006, the DOD has used hand-launched UAVs to fly over 400,000 hours of support missions for Operation Enduring Freedom and Operation Iraqi Freedom (DOD, 2007). The Navy used UAVs in the first Gulf War, with Pioneer UAVs performing

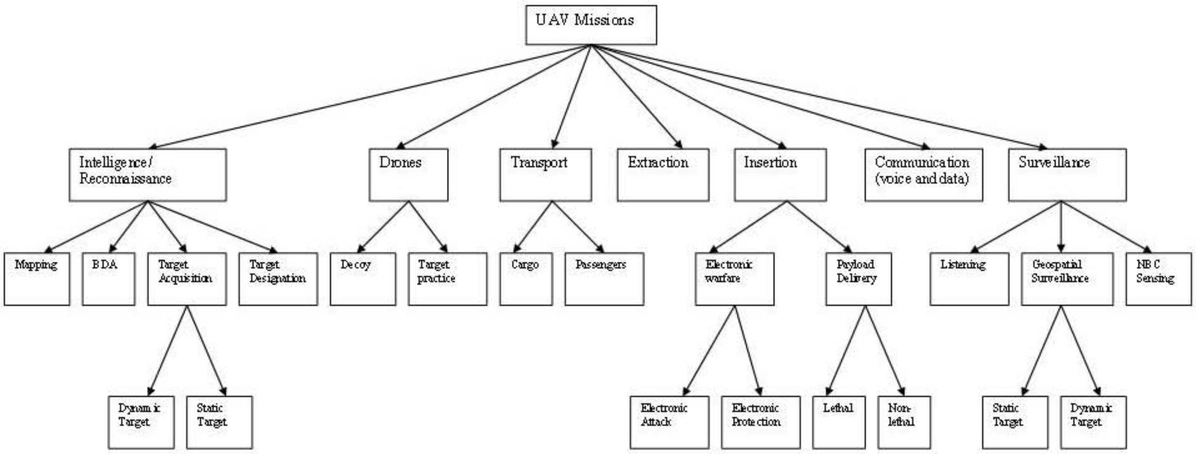


Figure 2-1: Possible UAV Missions (Nehme et al., 2007).

reconnaissance missions (Banks, 2000). Currently, the Navy is developing a vertical-take-off-and-landing tactical UAV (VTUAV), designated the MQ-8B Fire Scout. The Navy plans to have Fire Scout operational and throughout the fleet in fiscal year 2009 (Schroeder, 2008). The Army has 400 UAVs in theater for the Iraq and Afghanistan wars (Sullivan, 2008). Currently, the Army has 785 UAVs, comprised of Raven, Shadow, Hunter, and Warrior systems, with a proposed increase to 4,755 UAVs by 2023 (Sullivan, 2008). The Air Force, too, is transitioning toward the use of unmanned vehicle technology. Since 2001, the Air Force has reduced fighter inventory by 152 aircraft, while simultaneously increasing UAS platforms by 113, with intentions of continuing this over the next several years (Randolph, 2007).

There is a need for automation and technology to better support human involvement in managing these unmanned systems. From January to October 2007, the number of hours for mission sorties doubled for UASs in the Air Force, creating a manning crisis. Near the end of 2007, the Air Force shifted 120 pilots out of the manned cockpit to the ground control stations for UASs (Staff, 2008). A technological solution proposed by many DOD senior leaders and researchers to alleviate this manning crisis is to move from a team of operators controlling a UAV to having a single operator

controlling multiple UAVs (Barbato et al., 2003; Culbertson, 2006; Tsach et al., 2007). Figure 2-2 illustrates this transition.

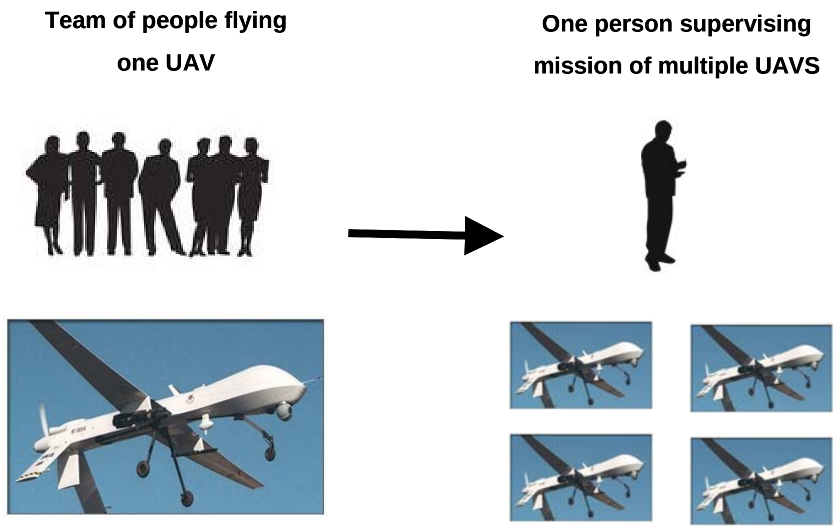


Figure 2-2: Transition to Multiple-UAV Supervision.

2.1.2. The Human in the System

The two terms UAV and UAS may appear interchangeable. However, there is a key distinction between them. The Office of the Secretary of Defense has issued the following definition:

> Unmanned Vehicle. A powered vehicle that does not carry a human operator, can be operated autonomously or remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload…Unmanned vehicles are the primary component of unmanned systems (DOD, 2007).

The key point is that the UAV is a sub-component that helps comprise the overall UAS. Another key sub-component to the UAS is the human operator controlling UAV operations through a ground control station.

The term unmanned does not imply removing the human completely because a human is still involved in unmanned operations, even in the most autonomous situation. The human's role is not eliminated just because the human is no longer co-located with the mission (DOD, 2007). Even as autonomy progresses, the need for

human reasoning and judgment will never be replaced within the UAS (Economist, 2007). Furthermore, the DOD has stated that humans are still necessary "to interpret sensor information, monitor systems, diagnose problems, coordinate mission time lines, manage consumables and other resources, authorize the use of weapons or other mission activities, and maintain system components" (DOD, 2007). Thus any UAS must be designed to support the role of the human operator in establishing the system's goal, supervising the system to guide it toward the goal, and ensuring mission success (Barbato et al., 2003; DOD, 2007). The human operator's supervisory role is essential to UAS operations. This thesis explores areas in which new technology can support the single, human operator in supervising the operations of multiple UAVs.

2.1.3. The UAV Ground Control Station

To support the supervision of UAS operations, an understanding of the current UAV ground control stations is needed. Today, the Air Force and Army operate most UAV missions from trailers or the backs of trucks. Most operations rely primarily on visual displays. In the Air Force, the solution for providing additional missing information to UAS operators has been to add more visual displays. However, humans have a limited capacity of resources to process information, so adding more visual displays will only further overload operators (Wickens et al., 2004). One solution explored by this research to help humans process more information is adding audio displays that can draw upon more attentional resources without adding significantly to the workload.

Operating in field conditions, UAS ground control environments can be very noisy and aurally cumbersome, with generators running in the background and required communication between inter and intra team members. This is significant to note when considering auditory displays. Any implementation of an audio alert in

these types of field conditions will have other audio alerts competing for attention and only certain available frequencies over which alerts can be generated and heard.

2.2. Attention Theories

The processes by which humans acquire and aggregate information for proper decision making and taking action rely upon attention resources (Parasuraman, Sheridan, & Wickens, 2000). Understanding these processes is important in the design of UAV supervisory control because various types and amounts of attention are needed for the multiple tasks performed by the UAVs. This section discusses different attention types and the allocation of attention resources that are used in human cognitive processing.

2.2.1. Selective, Divided, and Sustained Attention

The primary task for an operator overseeing multiple-UAV operations will be to simultaneously monitor particular tasks across multiple UAVs. This will require the UAV operator to time-share between the tasks to maintain continual awareness and respond at the appropriate time to each task. Further, the missions will occur over prolonged periods of time, during which the human operator will monitor for abnormal conditions and also provide high-level directives to the semi-autonomous UAV operations. Therefore, it is assumed that in the supervisory control role, UAV operators will primarily perform their role with selective, divided, and sustained attention.

Selective attention occurs when an operator must "monitor several sources of information to determine whether a particular event has occurred" (Sanders & McCormick, 1993). An example of selective attention in multiple-UAV operations is when a sensor operator is watching multiple UAV video feeds to locate a particular enemy vehicle.

Divided attention occurs when "two or more separate tasks must be performed simultaneously, and attention must be paid to both" (Sanders & McCormick, 1993). Continuing with the same example, the sensor operator may be forced to rely on divided attention if he is required to keep track of a vehicle he has located, as well as continuing to monitor the other video inputs for potential enemy vehicles that require some action. This type of attention requires a form of time-sharing, where the operator splits his time between tasks.

Sustained attention occurs when an operator "sustains attention over prolonged periods of time, without rest, in order to detect infrequently occurring signals" (Parasuraman, Warm, & Dember, 1987; Sanders & McCormick, 1993). This is generally the bulk of a UAV surveillance mission. The sensor operator in the previous example will spend a majority of his time simply watching for a change in the videos that would indicate an enemy vehicle.

2.2.2. Attention Resource Theories

To maintain a high level of performance, an operator must manage his attentional resources. A scarcity of resources exists, and this limited pool of resources is what is drawn upon by the various attention types (Wickens et al., 2004). Three hypotheses proposed in the literature (Hirst, 1986) to explain attention resources are as follows:

1. One central resource – a single resource from which all tasks draw.
2. Multiple resources – with some tasks drawing from some resource pools and not others. For example, verbal tasks draw from a verbal resource pool and not a visual resource pool.
3. Both a multiple resources pool as well as a central resource pool.

In general, these theories assume a scarcity of resources. The single resource theory holds that there is a single pool for attention resources that is drawn upon for all the mental processing (Kahneman, 1973; Moray, 1967). It proposes that humans have limited cognitive resources in this single pool and that when some of these resources are allocated, alternative tasks can only use what remains unallocated. There are some problems with the single resource theory. First, when a task is actually performed on a single processing code (e.g., verbal, spatial) or modality (e.g., visual, auditory), more attention resources appear to be required than when the task is performed using multiple processing codes or modalities. Second, within some groupings of tasks, if the difficulty of one task increases, there appears to be no effect on the other tasks. However, in groupings with similar tasks, when the difficulty of one task increases, it seems to affect the performance on the other tasks (Sanders & McCormick, 1993; Wickens & Hollands, 2000). There appears to be interference and failed time-sharing within certain task groupings, but not others. These problems indicate that perhaps there are separate attentional resource pools for the different processing codes or modalities.

2.2.3. Multiple Resource Theory

As opposed to the single resource theory, the multiple resource theory proposes that there are multiple independent pools from which attentional resources are drawn. As a result, there can be increased efficiency when time-sharing between multiple tasks (Sanders & McCormick, 1993). Interference, discussed in the single resource theory above, is a result of multiple tasks requiring resources from the same pool. Multiple resource theory propounds that information can be processed concurrently by dividing presentation over various channels so that the information is processed simultaneously by different pools of attentional resources (Wickens et al., 2004).

Multiple resource theory holds that the effect one task has on another depends on the type of tasks. An example is when someone tries rubbing his stomach while patting his head. This is difficult because he has run out of attentional resources, while speaking and rubbing one's stomach is completely possible because there are ample attentional resources. Wickens and Hollands (2000), in their model in Figure 2-3, explains why. Their model provides four dimensions to classify which resource pools attentional resources are coming from: stages, input modalities, processing codes, and responses. The example of patting one's head and rubbing one's stomach is an illustration of two manual responses, which require resources from the same pool. While rubbing one's stomach and speaking, respectively, are illustrations of manual and vocal responses. Because they are different response types, they have different attentional pools of resources to draw upon.

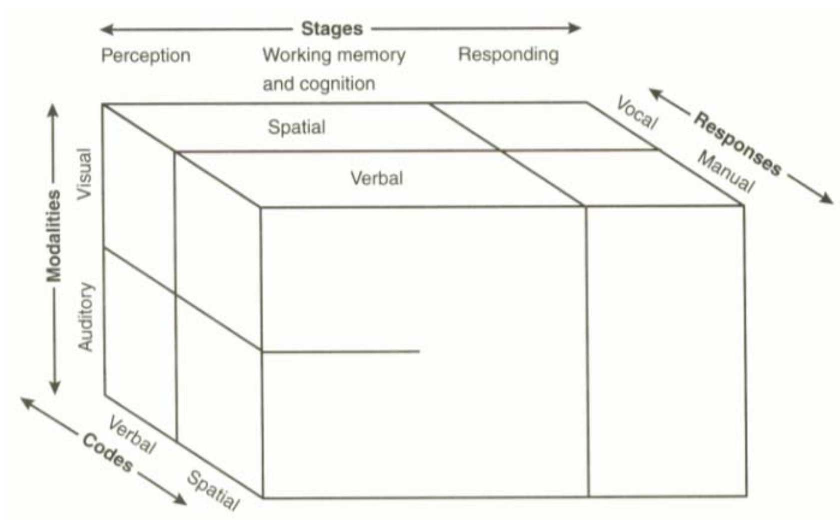


Figure 2-3: Attentional Resource Pools (Wickens & Hollands, 2000).

The focus of this thesis is on using aural and visual input modalities to aid in the multiple-UAV supervision task. Input modalities are the channels over which information may be presented to an individual. Research has shown that if a task's information is presented in dual coding, on differing modalities, such as the auditory and visual sensory channels, time-sharing is more efficient (Miller, 1991). In contrast, if

tasks are redundantly coded, on the same modality, such as the auditory and auditory or visual and visual sensory channels, interference occurs (Sanders & McCormick, 1993). Research by Streeter, Vitello, and Wonsiewicz (1985) showed human operators can better process aural commands for driving, while the drivers are focusing their visual attention on the road.

Previous research has shown that dual coding, i.e., displaying information on two separate modalities is beneficial (Miller, 1991; Streeter et al., 1985). For example, it has been found that using both visual and audio multimedia in unison is a useful way to present information (Mayer, 1999). Similarly, it should be beneficial to dual code information in both the visual and audio modalities to aid operators in monitoring UAV operations. The premise of this research is that by dividing the monitoring of tasks over multiple modalities, the operator will better be able to integrate all attentional resource pools toward efficiently controlling multiple tasks. In fact, this is not a new idea. In a meta-analysis of 43 previous studies (Burke et al., 2006), researchers concluded that in UAV operations dual coding information on the visual and auditory or visual and tactile modalities increases performance, while potentially decreasing workload. One study in the UAV domain compared a visual display with a visual display supplemented with an audio alert and found enhanced performance with the latter. This same study also showed that when going from supervising one UAV to supervising two UAVs, operator performance decreased, regardless of the display (Dixon, Wickens, & Chang, 2005). This thesis explores continuous audio alerts which have not yet been combined with visual displays for supporting UAV operators.

2.3. Audio Research

This thesis focuses on the use of continuous audio alerts, in particular, sonifications, in a multi-modal display to help an operator supervise multiple tasks

across multiple unmanned aerial vehicles. The existing audio literature is approached from three perspectives. First, audio research for supervisory control with multi-modal displays is reviewed to help frame what types of supplemental audio displays have not been researched for application with UAV supervisory tasks. Second, a form of audio that has not been extensively researched in its ability to aid supervisory control is continuous audio. For this reason, a review of applicable continuous audio research is completed. Third, a form of continuous audio that portrays relations in information and information changes is sonifications. In closing this section, a review of key supervisory control sonifications research is accomplished.

2.3.1. Supervisory Control with Multi-Modal Displays

A significant body of audio research applicable for supervisory control of multiple unmanned vehicles focuses on spatial audio (Nehme & Cummings, 2006). Spatial audio is 3-dimensional (3D) audio in which audio is presented so that specific signals come from specific locations in the 360-degree range around someone's head. An example is an audio alert for one UAV presented over a headset directly in front of the operator, while alerts for another UAV are connected to signals directly behind the operator.

The spatial audio research applicable to supporting operators performing supervisory tasks has primarily focused on sound localization (Martin, McAnally, & Senova, 2001; Wightman & Kistler, 1989), detection and localization of visual targets (Bolia, D'Angelo, & McKinley, 1999; Bronkhorst, Veltman, & vanBreda, 1996; Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998; Nelson et al., 1998), collision avoidance (Begault & Pittman, 1996), and navigation (Moroney et al., 1999). In the aviation domain, this research has primarily been applied in the manned cockpit; because of the supervisory nature of these tasks, this research is applicable in the unmanned cockpit as well. In particular, spatial audio has been shown to help reduce search times and

produce faster response times for target acquisition (Parker, Smith, Stephan, Martin, & McAnally, 2004) and alert and warning detection (Begault & Pittman, 1996). The literature suggests that spatial audio helps mitigate visual change blindness effects, which occur when an operator is so focused visually on one task that the operator's focused attention causes another visual warning to be missed (Nehme & Cummings, 2006). Outside of spatial audio, little other audio research has been done in the supervisory domain of multiple UAVs. In combing the audio literature, little applicable research is found where ambient noise headphones and associated filtering techniques are used to support a supervisory task in a multi-modal display (Nehme & Cummings, 2006). A form of this audio is continuous audio, which is explored next.

2.3.2. Continuous Audio

Continuous audio alerts play continually to map information on the state of a task. The contrast to continuous audio is discrete audio, which only plays at a discrete point in time when a task's state changes. Discrete audio can be used to aurally interrupt an operator to notify him of a problem. Continuous audio is essentially a peripheral monitoring system, which allows the operator to constantly monitor for abnormal situations; in this case, an operator is using divided attention to time-share their focus between performing or monitoring multiple tasks, with the audio as a cue guiding when to shift focus.

Most audio alert research has focused on discrete alerts in the forms of a "beep" and "ding" (Brewster, Wright, & Edwards, 1994). However, a limited number of formal human studies have investigated continuous audio alerts (Pacey & MacGregor, 2001). The continuous audio research that has been completed has focused on using continuous audio and discrete audio alerts to enhance a visual display for a monitoring task. Research has shown the addition of continuous audio with a visual representation enhances operator performance (Crease & Brewster, 1998; Pacey & MacGregor, 2001).

The following paragraphs will discuss the details of these experiments that have been run with continuous audio.

One of the first experiments run with human participants was by Crease and Brewster (1998). Participants completed a primary task of typing poems, while monitoring the downloading of files as a secondary task. Participants had either a visual progression display of the downloading or a visual and auditory progression display. The results of the experiment showed that participants with the continuous audio display were significantly quicker at responding than the participants with only the visual display. This is an example of how displaying the information on multiple modalities enhanced operator performance for a monitoring task.

In a similar experiment, Pacey and MacGregor (2001) compared a baseline visual display with the visual display plus one of three different audio displays: discrete chimes, continuous wind, and a continuous audio progress bar. The primary difference between the audio displays was the amount of information presented by the display. The discrete chimes presented two of the task's properties, i.e., when a task began and when the task ended, with separate discrete chimes that played when an event began and when an event ended. The continuous wind was a low wind noise that played continually from when a task began until it ended. It added a third piece of information; as long as the wind was playing, the operator knew that the task was still occurring. The continuous audio progress bar presented six of the task's properties, such as scope, initiation, progress, heartbeat, remainder, and completion, through continuous audio created by different arrangements of 12 different notes; this audio played continually throughout an event. While the results were mixed dependent upon what performance metrics were considered, it is clear that adding the audio alert to the visual display significantly enhanced the participants' ability to complete the primary and secondary tasks. Pacey and MacGregor's findings showed that when simply considering the reaction times for catching the downloads ending, the audio progress

bar was significantly better than the chimes, but that the chimes were significantly better than the wind or visual-only display. However, as indicated by the primary task metrics, typing speed and accuracy, participants using the chimes performed significantly better than the auditory progress bar or visual-only display. The conclusion, therefore, is that the chimes provided the best results of enhancing the ability to perform the secondary task of catching download endings, without hampering the primary task of typing poetry.

With Pacey and MacGregor's mixed results on the effects of discrete versus continuous audio support on both a secondary and primary task, this thesis will further explore whether monitoring tasks in supervisory control is better supported by a typical discrete audio alert or a by a continuous audio alert. Further, this thesis will explore using both discrete audio and continuous audio in a single audio condition to support multiple supervisory tasks. Because of the limited research available on continuous versus discrete audio, the results of this thesis will be an important contribution to the audio alert research.

2.3.3. Supervisory Control Sonifications

Continuous audio is defined above as audio alerts that play continually to provide continual information on a task's state. Sonifications are a form of continuous audio, in which data and relations in data are mapped to relations in the audio display (Kramer, 1994). An example of a sonification that Tannen (1998) gives is sonar on a submarine that indicates the distance of a torpedo. As the torpedo gets closer, the sonar beeps become more intense on a continual scale. The intensity of the beeps provides relational data of how far the torpedo is from the submarine. Sonifications are a subset of continuous audio. The torpedo example is sonification in particular, because the intensity of beeping noise provides the relational data of how far the torpedo is from the submarine.

Research has shown sonifications to be beneficial in medical and assistive technologies, scientific visualizations, engineering analysis, emergency alerts, and aircraft cockpits (Barrass & Kramer, 1999). One example in the medical domain is a study by Loeb and Fitch (2002) that compared three types of anesthesiology displays: visual only, auditory only, and a combined visual and auditory display. The task for participants was to monitor if any of six vital signs exceeded normal limits. For the auditory displays, participants received independent streams of audio for the vital signs. For the heartbeat, the audio was a low-pitched, repetitive, thudding to resemble what one may envision the heart sounding like. For the respiratory system, a higher-pitched amplitude-modulated signal was used. For the remaining four vitals, variations of modulation and filtering were used to generate the audio. The participants with the combined visual and audio display had the quickest reaction times, but the visual-only display produced the most accurate reactions.

In a similar anesthesiology study, Watson and Sanderson (2004) asked participants to divide their attention between monitoring for an abnormal event and performing some other primary task. Thus, monitoring was a secondary task. In particular, they tested various modalities in supporting anesthesiologists and non-anesthesiologists in monitoring a respiratory rate as the secondary task. There were three displays tested: sonifications only, visual only, and combined sonifications and visual. The sonifications were respiratory sonifications in which the breathing rate was mapped to a pure tone with musical notes on the third interval, for inhalation and exhalation. Watson and Sanderson (2004) results illustrated that regardless of the display modality, the performance was the same for the secondary task of monitoring the breathing, but that for the time-shared primary task, participants performed best with the combined display. These results show the benefit of the combined display in helping participants time-share. However, because only sonifications were used as the audio support in these experiments, there is no comparison between sonifications and

discrete audio. This comparison is what this thesis will explore. Further, these results are limited in that they only tested the effect of the displays on an anesthesiologist monitoring a single patient. This thesis will analyze the benefits of sonifications while monitoring multiple tasks (UAVs) as opposed to a single task.

2.4. Research Hypotheses

Having framed the research of this thesis, two hypotheses are proposed. The first hypothesis is that in comparison with a discrete audio scheme, continuous audio, in the form of a sonification, improves operator performance for monitoring sustained and divided attention tasks in a time-intensive dynamic environment. Continuous audio reduces the uncertainty of a future state by allowing operators to monitor trends in a changing state over a secondary modality. Further, by placing this information over the audio channel, there is immediate access to the information. Immediate information access is important to performance because humans tend to re-check signals repeatedly because of limited human memory (Moray, 1981).

The second hypothesis is that the benefits of continuous audio will be more beneficial for operators controlling multiple vehicles rather than a single vehicle, since the workload under the multiple case is significantly higher. Because the monitoring of multiple vehicles increases workload, more attentional resources are required from supervisors. The addition of the audio displays to the visual display provides an additional pool from which to draw attentional resources for processing some of the information for managing the UAVs. Furthermore, the continuous audio allows for more information to be presented over the audio sensory channel than the discrete audio because it provides a continual status. Because it provides more information than the discrete audio, the expectation is that in a high workload situation, where the attentional resources are fully utilized, the additional continuous audio will allow

operators to draw more attentional resources from the audio resource pool, which will better support their performance.

To test these hypotheses, a multiple-UAV simulator experiment was conducted, which will be discussed in more detail in Chapters 3 and 4.

3. Simulator and Interface Design

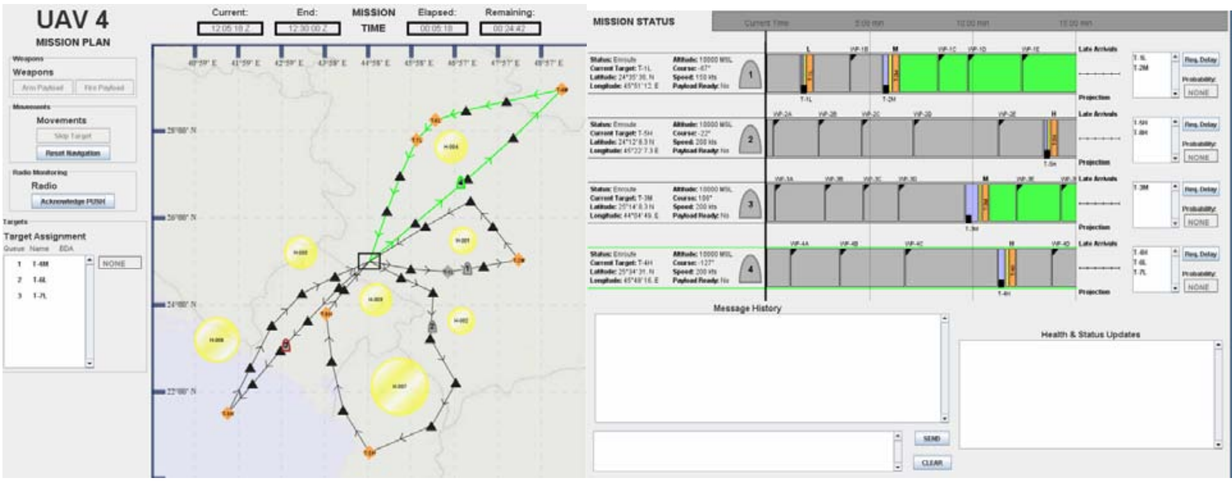
The Multiple Aerial Unmanned Vehicle Experiment (MAUVE) test bed was developed in previous research to allow human operators to perform supervisory control tasks as they monitor the progression of multiple UAVs arming and firing on targets, performing battle damage assessment, and avoiding threat areas (Mitchell, 2005). The following sections will present how MAUVE was customized for this experiment and the form of the audio displays that were created and integrated into the MAUVE interface for this experiment.

3.1. Multiple Aerial Unmanned Vehicle Experiment (MAUVE) Test Bed

MAUVE is a two screen interface that allows the simulation of any number of UAVs conducting strike operations in hostile environments. MAUVE, for this experiment, allowed the operator to arm and fire on targets with various priorities, while monitoring each UAV's flight of path, event timeline, and radio traffic.

The MAUVE test bed provided a map for geo-spatial tracking of UAVs on their preset flight paths, along with an interaction control panel for making UAV control inputs (Left Display, Figure 3-1). Control inputs included arming and firing a UAV to destroy targets, directing specific path changes, and acknowledging radio calls. For each control input, operators simply clicked one or two buttons on the control panel (Figure 3-2).

A timeline for each UAV, a scheduling decision support visualization (DSV) for each UAV (which will be discussed in detail in a subsequent section), and chat interfaces were also provided (Right Display, Figure 3-1). This timeline display helped operators ensure UAVs would be on time to targets by monitoring when UAVs would arrive at targets and in what phase of the mission they were currently located. In



Map Display **Timeline Display**

Figure 3-1: Multiple Aerial Unmanned Vehicle Experiment (MAUVE) Test Bed.

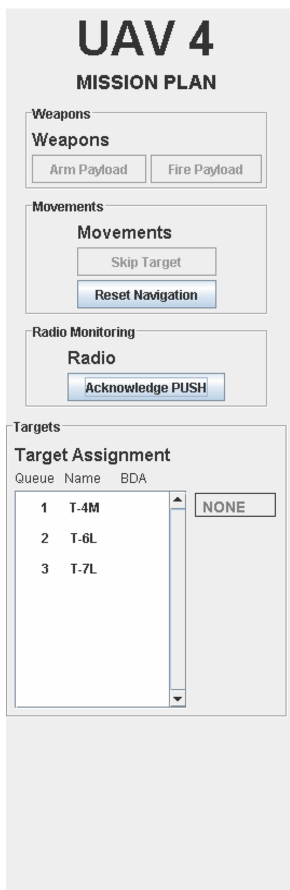


Figure 3-2: UAV Interaction Control Panel

Table 3-1: UAV Color-Coded Flight Phases

UAV Action	**Color**
Enroute	Gray
Loitering	Blue
Arming Payload	Yellow
Firing Payload	Orange
Return to Base	Green

particular, the timeline used the color-coding provided in Table 3-1 to represent the phase of flight.

The general task for MAUVE operators for this experiment was to monitor one or more UAVs on a preplanned mission involving several waypoints and targets. The primary task of the operator was to ensure weapons were dropped on the correct targets during the specified windows of opportunity. However, unexpected head winds or crosswinds could cause UAVs to slow their speed or drift off course, requiring the operator to take corrective action for projected target late-arrivals or course-deviations. Late-arrivals were a higher priority than course-deviations. In addressing late-arrivals, the priority of the target (high, medium, or low) also had to be addressed, because a high priority target was more important than a medium priority target, and so on. In addition, operators also had to ensure the UAVs would return to base by a specified time.

Figure 3-3 provides the visual representation for a late-arrival. A black rectangle on the timeline showed when the UAV was going to arrive at the labeled target, and it changed from black to red when the UAV was going to be late. This could also be seen when the black rectangle moved past the orange window of opportunity. On the timeline below, the red rectangle labeled "T-1L" indicates that the UAV will be late to

target T-1L. In contrast, the black rectangle labeled "T-2M" indicates that the UAV will be on time to target T-2M.

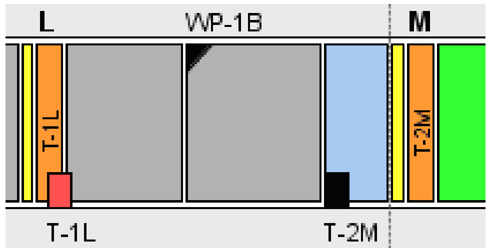


Figure 3-3: Late-arrival Illustration.

The decision support visualization (DSV) was an additional visual tool used when a UAV was late to a target. The DSV was designed to illustrate the current state of a UAV and the projected future *what-if* states of a UAV. The DSV was located at the right edge of each UAV's timeline in the Timeline Display (Figure 3-1). For example, the DSV in Figure 3-4 illustrates that the UAV is late to a high priority target by having a dark gray rectangle with an H in the rectangle's center in the late-arrivals section of the DSV. After the operator checks the timeline and sees that the UAV is going to be late to T-7H, he highlights T-7H on the DSV, posing a *what-if*. The DSV now shows the projected future state in the projection section. If target T-7H's time on target is delayed, the UAV will still be late to a high priority target. The light gray rectangle with the H within the rectangle of Figure 3-4 illustrates that the UAV will still be late to a high priority target.

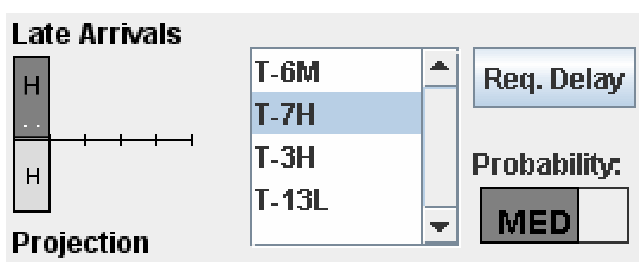
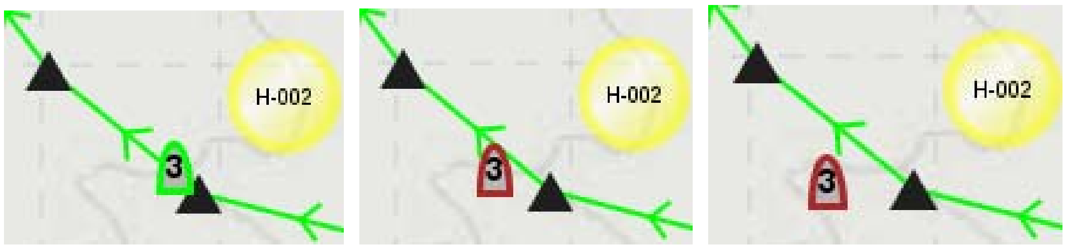


Figure 3-4: Decision Support Visualization (DSV)

The green line in Figure 3-5 indicates the plotted and desired flight path. Anytime the UAV completely departed from the green course line, the UAV was

considered to have deviated. During the simulation, the UAV constantly fluctuated back and forth on the flight path, but participants were trained to respond when the UAV actually was no longer touching the course line. Below are images illustrating UAV 3 on course, almost off course, and off course.



On Course **Almost Off Course** **Off Course**

Figure 3-5: Course-deviation Illustration.

Two tasks were selected in MAUVE for continuous audio (sonification) representation. Both were secondary monitoring tasks, and both were also intertwined with the primary task in a way that the secondary task had to be completed for the primary task, firing on the various targets on the flight path, to be successfully achieved.

The first secondary task was monitoring for late-arrivals to targets. Each target was either a high, medium, or low priority target. On time arrivals and late-arrivals to high, medium, or low priority targets were four discrete events to which the continuous audio had to be mapped. Continuous audio could be used to represent the state of UAVs in that the audio would play continually, indicating which of the four states a UAV was in at any point in time. In particular, for this setup the continuous audio was modulated so that it would convey the priority of the target to which one was late. For example, as will be discussed later, there were modulated increases in the audio to indicate a high priority target in contrast to a low priority target. That is what made this a sonification.

Monitoring for course-deviations was the other event to which continuous audio was mapped. This was an ideal continuous event in that the UAV could start on course

but then on a continual scale progress away from the course line. Again, this changing continuous audio was mapped to the rate of change with which a UAV traveled off course, making the audio a sonification.

3.2. Four Auditory-alerts

Four auditory alarms were created to test the effect of discrete and continuous alarms in helping operators monitor for late-arrivals and course-deviations in MAUVE. Presented in Figure 3-6, these four auditory-alerts were 1) an oscillating course-deviation alert, 2) a modulated late-arrival alert, 3) a threshold course-deviation alert, and 4) a threshold late-arrival alert.

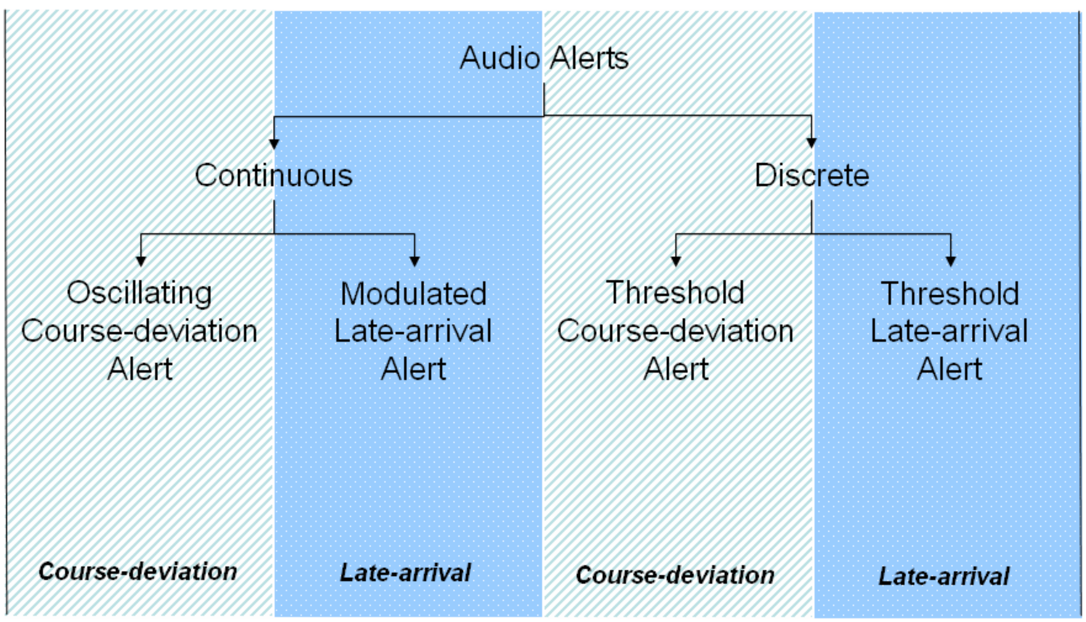


Figure 3-6: Four Auditory-alerts.

The oscillating and modulated alerts were continuous alarms; they provided continual audio information about the state of a particular variable within the simulator. Instead of indicating a clear distinct threshold, the oscillating and modulating alerts gradually increased as the severity of either the late-arrival or course-deviation condition increased. The threshold alerts were designed to be discrete

alarms; they emitted a single discrete audio alert when some precondition was met. These four auditory alerts were presented to MAUVE operators through the HDiSP (Headset Display), which will be discussed further in the next section.

3.3. Sensimetrics HDiSP

All audio alerts were presented equally in both ears through the Sensimetrics HDiSP[1]. Pictured in Figure 3-7, the HDiSP is an over-the-head headset with sealed around-the-ear ear cups. The HDiSP provides ambient noise attenuation ranging from 35 to 40 dB for the spectrum between 500 and 8 kHz. The headset has integrated digital signal processors, which produce the signals used in this experiment based on generative audio filters and processing of the ambient signal, which was received from microphones mounted on the headband. The next section will provide the technical description of how each alert was displayed.

Figure 3-7: Sensimetrics Headset Display (HDiSP).

3.4. Technical Description of Auditory-alerts

The auditory-alerts created for this experiment were generated through collaborative work between MIT's Humans and Automation Laboratory and Charles

[1] Contact Dr. Thomas Edward von Wiegand, at tew@sens.com, for further information on the Sensimetrics HDiSP.

River Analytics, Inc. The primary consideration in designing the audio alerts was to create audio that would capture the human operator's attention and effectively convey the necessary information to the operator. To design to these parameters, there were a few guidelines followed Deatherage (1972) and Sanders and McCormick (1993)). Appendix A has a compilation of the design principles. Further, each audio alert was designed to always alert to the worst condition. Therefore, in the multiple-UAV condition, where multiple UAVs could be having course deviations, the audio alert played for whichever UAV currently was furthest off course.

The oscillating course-deviation alert represented both the existence and severity of the UAV course-deviations. The alert consisted of comb filters that were applied to a mix of pink noise and the ambient signal. Using pink noise means that filters equalized the energy of sound at each octave level, resulting in a constant level presentation of the audio. The mix ranged from 0.2 pink noise for low deviation to 0.9 pink noise for high deviation. The comb filters had a base delay of 0.2 ms, with a 50 percent mix of the base signal and a feed forward delay. The delay values were then oscillated to create a periodic signal. Because this was a continuous audio scheme, the oscillating course-deviation alert played continually to provide an auditory image of UAV path position. As a UAV drifted further off course, the frequency of oscillation of the comb filter delay decreased from 17 Hz to 4.5 Hz, and the depth of oscillation increased from 0.2 ms to 0.7 ms, on a continual scale.

The threshold course-deviation alert consisted of a single beep with a fundamental frequency of 1000 Hz. The beep lasted around 8 ms and played whenever a UAV moved completely away from the UAV's plotted course line.

The modulated late-arrival alert consisted of discrete harmonic signals continuously playing to indicate a projected late-arrival at a target. These sounds played continually until the operator addressed the issue with the corrective action of choosing to delay the UAV, skip a target, or the issue disappeared because the UAV

automatically continued past the target when the UAV was going to be late to the next target. The harmonic signals were composed of five Formant filters that were applied to a mix of pink noise and the ambient signal. During the condition of no late-arrivals, a baseline audio condition was generated with two filters set to 261.6 Hz, two filters set at 329.4 Hz, and one filter set at 392.0 Hz (a major C triad with extra balance in the root and third). If the UAV was late to a low priority target, a signal was generated with two filters set to 261.6 Hz, two filters set at 311.1 Hz, and one filter set at 392.0 Hz (a minor C triad with extra balance in the root and third). If the UAV was late to a medium priority target, a signal was generated with three filters set to 293.6 Hz and two filters set at 415.3 Hz (a tritone interval with a D root). If the UAV was predicted to be late to a high priority target, a signal was generated with three filters set to 369.9 Hz and two filters set at 523.25 Hz (a tritone interval with an F# root). As the priority increased, the pink noise mix also increased, from 0.25 for the baseline, to 0.7, 0.8, and 1.0 for the three priority levels.

Differing from the threshold course-deviation alert, the threshold late-arrival alert consisted of a single beep with a fundamental frequency of 415 Hz, instead of 1000 Hz. In addition, the beep lasted around 18 ms, instead of 10 ms, and played whenever a UAV was projected to be late to any target. A UAV was determined late to a target when the UAV had exceeded the UAV's window of opportunity to destroy the target and was not going to be able to get over the target in time to fire on it during the allotted time window in which the UAV was required to be at the target.

4. Methods

After integrating the audio alerts discussed in Chapter 3, *Simulator and Interface Design*, into MAUVE, an experiment was conducted to compare continuous audio and discrete audio alerts in aiding single operator awareness in controlling multiple unmanned vehicles. This chapter will review the experimental questions, the setup of the experiment, and the design of the experiment for evaluating the research questions.

4.1. Experimental Questions

The objective of this experiment was to determine whether continuous audio helps maximize the information conveyed to UAV operators more efficiently than discrete alarms, which are typically used in current ground control stations. In addition, the impact of continuous versus discrete alerting on operators moving from control of single to multiple UAVs was also a research question.

To explore these objectives, two null hypotheses were tested in this research:

1. For various combinations of discrete and continuous alerts, there is no difference in the operator's performance.
2. There is no interaction between the discrete and continuous alert combinations and whether the operator is controlling one or multiple UAVs.

The alternative hypothesis for the first null hypothesis, therefore, was that there is a difference, and for the second null hypothesis, that there is an interaction.

4.2. Experimental Apparatus

The experiment was administered in a testing room with a background ambient noise level of ~64dB on a C-scale. MAUVE was run on a multi-modal workstation (MMWS) (Osga, VanOrden, Campbell, Kellmeyer, & Lulue, 2002). Pictured in Figure 4-1, the MMWS is a four-screen computer display.

Figure 4-1: Multi-Modal Workstation (MMWS) (Osga et al., 2002).

The three screens across the top were 21 inches and set to display at 1280 x 1024 pixels, 16 bit color resolution, and the 15 inch bottom center screen was set at 1024 x 768 pixels, 32 bit color resolution. The computer used to run the simulator was a Dell Optiplex GX280 with a Pentium 4 processor and an Appian Jeronimo Pro 4-Port graphics card. Participants controlled the simulator through a generic corded computer mouse. Throughout the experiment, the top left display showed the mission objectives and priorities, and the bottom center one displayed the color-coding for MAUVE (Table 3-1). The top center display contained the left MAUVE map and interaction display, and the top right display included the right MAUVE timeline and decision support display (Figure 3-1).

For this experiment, the operator was given the following as the primary objective for each mission: Make sure the UAV(s) maximize the number of targets engaged as well as arrive back at the base safely.

Further, supervision of each of the UAV(s) for each mission was broken down into the following prioritized sub-tasks, from highest priority to lowest:

1. Return to base (RTB) within the time limit for the mission (this limit was clearly marked).
2. Comply with recovery rules for course-deviations.
3. Comply with recovery rules for target late-arrivals.
4. Destroy all targets before their time on target (TOT) window ends..
5. Avoid taking damage from enemies by avoiding all threat areas.
6. Acknowledge all "Push" radio calls.

Participants were trained to follow these priorities, and the objectives and priorities above were displayed to them throughout the experiment. Within the priorities, recovery rules of how to recover the UAV from a course-deviation or late-arrival were also displayed. The instructions on how to comply with recovery rules for course-deviations were to click "Reset Navigation" on the control panel (Figure 3-2). This theoretically reset the onboard navigation in the UAV and caused that UAV to fly back to the planned flight path.

The instructions on how to comply with recovery rules for target late-arrivals were as follows:

- Low Priority – Click "Skip Target."
- Medium Priority – Click "Skip Target" or employ the decision support visualization (DSV).
- High Priority – Employ DSV before requesting delay or clicking "Skip Target."

For low priority targets, clicking the "Skip Target" button on the control panel (Figure 3-2) would cause the UAV to proceed immediately to the next target. For medium and high priority targets, the option was given to use the DSV. As discussed in Chapter 3, *Simulator and Interface Design*, the DSV (Figure 3-4) is a tool that illustrates the effect that delaying the time on target for one late target has on the remaining targets for that UAV's flight plan. With the assistance of the information presented in the DSV, participants then decided whether they should click the "Skip Target" button or the "Request Delay" button on the DSV. If they clicked "Request Delay," participants then had to wait to see if a delay was granted, and if the delay was granted, the UAV was then no longer late to the target and would be able to destroy the target. For a high priority target, the immediate response was to employ the DSV.

4.3. Experimental Design

4.3.1. Independent Variables

The experiment was a 4x2 fixed factor repeated measures model, with two independent variables: the audio condition (a between-subjects treatment), and the number of vehicles under control (a repeated within-subjects factor).

The four levels of the audio condition factor were combinations of the four auditory-alerts described earlier in Figure 3-6 in Chapter 3, *Simulator and Interface Design*. Every participant was exposed to two of the alerts shown in Figure 3-6. Participants were presented one audio alert from the course-deviation columns, either the oscillating course-deviation alert or the threshold course-deviation alert, and one audio alert from the late-arrival column, either the modulated late-arrival alert or the threshold late-arrival alert. The four audio conditions were the following: (1) the threshold audio condition for both the late-arrivals and course-deviations (BothThresh),

(2) the continuous oscillating course-deviation audio condition, with threshold alert for the late-arrivals (DevCont), (3) the continuous modulated late-arrival audio condition, with a threshold alert for course-deviations (LateCont), and (4) the both continuous audio condition, which consisted of the oscillating course-deviation alert and the modulated late-arrival alert (BothCont).

The second independent variable, the number of vehicles under control, had two levels: single-UAV and multiple-UAV. In the single level, the participant supervised only one UAV, while in the multiple level, the participant supervised four UAVs. The framework of this experiment is represented in Table 4-1.

The experiment was counterbalanced; a random half of the participants completed the single-UAV scenario first, and the other half finished the multiple-UAV scenario first. Additionally, the participants were randomly assigned to the four audio schemes to avoid confounding effects.

Table 4-1: Experimental Conditions

		Scenario (Repeated)	
		Single-UAV	**Multiple-UAV**
Audio Scheme (Between)	**BothThresh** **Threshold Course-deviation, Threshold Late-arrival**	Participants 1-9	Participants 1-9
	DevCont **Oscillating Course-deviation, Threshold Late-arrival**	Participants 10-19	Participants 10-19
	LateCont **Threshold Course-deviation, Modulated Late-arrival**	Participants 20-29	Participants 20-29
	BothCont **Oscillating Course-deviation, Modulated Late-arrival**	Participants 30-39	Participants 30-39

4.3.2. Dependent Variables

Dependent variables included the number of missed course-deviations, the reaction time to correct course-deviations, the number of missed late-arrivals, the reaction time to correct projected late-arrivals, the number of missed radio calls, and the NASA TLX scores. These are discussed in detail below.

4.3.2.1. Course Deviation Errors of Omission

In each test scenario, participants were expected to respond to four triggered course-deviations. See Appendix B for a timeline of the events for both the single and multiple-UAV scenarios. Again, as illustrated in Figure 3-5, a course-deviation was defined as a UAV no longer appearing to follow its planned flight path. Anytime the participant failed to respond to one of four triggered course-deviations, an error of omission was counted. This simply meant that the participant failed to recognize and address one of the four cued course-deviations before the UAV self-corrected. In the event that a course-deviation was missed, this data point was treated as a missing data point for calculating the course-deviation reaction times.

4.3.2.2. Course-deviation Reaction Times

The reaction time for a course-deviation event was the time taken by the participant to make a corrective input after one of the four course-deviations had been triggered. The course-deviation reaction time used for data analysis was an average of the reaction times for the course-deviations that the participant responded to per test scenario.

4.3.2.3. Late-arrival Errors of Omission

Four late-arrivals occurred in each test scenario. Illustrated in Figure 3-3, late-arrivals were caused when a UAV slowed down because of unforeseen headwinds and was no longer able to reach a target in time to complete the firing mission. Errors of

omission for late-arrivals occurred when the participant failed to respond to one of the four triggered late-arrivals. This simply meant that the participant failed to recognize and address the late-arrival before the UAV automatically moved past the target. In the event that a late-arrival was missed, this data point was treated as a missing data point for calculating the late-arrival reaction

4.3.2.4. Late-arrival Reaction Times

The late-arrival reaction time was the time taken by the participant to make a corrective action after one of the four late-arrivals was indicated. The late-arrival reaction time used for data analysis was an average of the reaction times for the late-arrivals that the participant responded to per test scenario.

4.3.2.5. Secondary Workload Assessment (Radio Calls Missed)

As a secondary workload task, the number of missed radio calls was an indication of the operator's level of mental workload. The count of missed radio calls measured spare mental capacity. Participants were instructed to monitor a recording of continual air traffic radio chatter for the word "Push." The word "Push" occurred 62 times in a 30 minute session, with an average of 27 seconds between each "Push" radio call. To acknowledge the radio call, participants clicked an "Acknowledge Push" button on the display (Figure 3-2).

4.3.2.6. Subjective Workload Assessment (NASA TLX Score)

The National Aeronautics and Space Administration (NASA) Task Load Index (TLX) gathered participants' subjective assessment on a scale of 1 to 20 of mental demand, physical demand, temporal demand, effort, performance, and frustration. A participant was then asked to rate these six dimensions against each other to determine their importance in the participant's workload (Hart & Staveland, 1988). Since there was

no physical demand in this experiment, each participant was told to rate the physical demand so that it was zeroed out of the score.

4.4. Participants

Given an a priori power analysis for a power of 0.80, the estimated minimum number of needed participants was determined to be 23, and 44 were recruited. Each participant was paid $10 an hour to participate. The experiment took between 2.5 and 3 hours to complete. Participants' ages ranged from 20 years to 42 years, with an average age of 26 years and standard deviation of 6 years. There were 3 Navy midshipmen, 1 Army reservist specialist, 1 Air Force staff sergeant, and 39 officers from the Army/Navy/Air Force. Overall, the personnel tested had a combined experience of over 250 years of active duty military service, with each member having an average of 5.8 years of active duty service. Five pilots contributed as test participants, and most of the 28 junior officers tested will be future military pilots. Overall there were 7 female and 37 male participants.

For the data analysis, 5 participants were dropped because of problematic data. The first two were omitted because of the failure of the test proctor to administer proper training. The third was dropped because of a 3 day interruption between the single-UAV and multiple-UAV test sessions. The fourth participant was not used because his secondary task data (i.e., number of push call responses) was an outlier of more than 3.29 standard deviations from the mean for both the single-UAV and multiple-UAV scenarios. The fifth participant dropped was an active duty Air Force lieutenant colonel with 4 years experience as a maintenance officer and an additional 4 years of flight line time as a pilot and flight test engineer. He reported having been diagnosed with tinnitus and loss of high frequency tone in one ear. During the audio training, he reported not being able to hear the differentiation between a low and high course-

deviation with the oscillating course-deviation alert. His hearing test results indicated age-induced hearing loss.

4.5. Testing Procedures

Each participant experienced three separate consecutive phases in completing the experiment. Each had a 60 to 70 minute training session, followed by a 70 to 80 minute test session and then a 10 minute post-test survey. For the training session, each participant completed a consent form and demographics survey, received standardized training from a PowerPoint® tutorial, a hearing test, audio training for the specific audio test condition, and a thirty minute practice test session with a trial run of the NASA TLX. If required, a participant could do an additional 10 minute practice session to ensure understanding of the proper MAUVE control actions. Copies of the participant consent form, demographics survey, tutorial, and post-test survey are in Appendices C, D, E, and F, respectively.

The hearing test was designed to identify whether the participant suffered any hearing loss (either temporary or permanent). For the hearing test, participants listened to a CD of test tones from 40dBSPL down to 16dBSPL, with 5 frequencies tested (500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz). Participants acknowledged how many beeps were heard in each ear and each frequency. The range tested ensured participants could hear to within 3dB of the noise floor of the headset in the normal lab conditions. Based on the method of descending limits, the test was designed so that hearing 5 beeps or more at each frequency showed adequate hearing (Snodgrass, 1975; Wundt, 1902). If fewer beeps were heard at 8 kHz than at 1 kHz, the participant exhibited high frequency loss (Cooper & Owen, 1976; Humes, Joellenbeck, & Durch, 2006). Age-related permanent loss showed up most at high frequencies (i.e. 8 kHz congestion and other losses show up at lower frequencies and across range) (Walden, Prosek, &

Worthington, 1975). The hearing test was generated by Dr. Thomas Edward von Wiegand of Sensimetrics Corporations, in conjunction with the HDiSP.

The audio training gave each participant exposure to all of the audio alerts each participant would hear. Participants were presented with their respective late-arrival and course-deviation alerts, as well as the radio chatter. After introducing each of these individually, they were played to provide examples of real test scenarios. After a demonstration of the audio condition, participants were encouraged to play with the audio demonstration software until they were comfortable with recognizing each of the alerts.

After the training was completed, each participant then completed both the single-UAV scenario and the multiple-UAV scenario. At the conclusion of every test session, MAUVE generated a data log, with all the previously discussed dependent variables. Additionally, participants completed a NASA TLX following each test session. At the conclusion of the test session, each participant completed a post-test survey, was paid, and thanked for his time and involvement.

4.6. Data Collection

For the collection of the data, all pertinent action sequences in MAUVE, such as the reaction times to correct course-deviations and late-arrivals and the radio call acknowledgements of the "Push" radio calls, were recorded in a MAUVE data file for each scenario. In addition, an Excel® file with the NASA TLX score was generated and saved for each scenario, and a Camtasia® video recording screen capture of the two MAUVE displays was saved.

5. Results

For statistical analysis, repeated measures analysis of variances (ANOVAs) were conducted for each dependent variable. The audio scheme factor was a between-subjects factor for the four audio conditions, and the scenario was a repeated within-subjects factor of single-UAV versus multiple-UAV levels. Excluding the late-arrival reaction times and error of omission counts which were non-parametric, all of the remaining variables analyzed met normality and homogeneity assumptions. While α was set to 0.05, p values between 0.05 and 0.10 were considered marginally significant. See Appendix G for further details on the statistical analysis tests.

5.1. Course-deviation Errors of Omission

Out of the 156 course-deviations presented to the 39 participants, 9 course-deviations were missed (5.8%). Of the missed course-deviations, approximately half (4 course-deviations) were missed by participants in the LateCont audio condition. The data was not normal, and the non-parametric tests (Kruskal-Wallis) showed no significant differences between the different audio conditions.

5.2. Course-deviation Reaction Times

Figure 5-1 shows the means for the course-deviation reaction times across the four audio conditions (BothThresh, DevCont, LateCont, and BothCont), with standard error bars. The omnibus test shows there was a statistically significant difference in the performance of participants based on the audio scheme ($F(3,35)=2.878$, $p=.05$), and a marginally significant difference due to the scenario ($F(1,35)=3.215$, $p=.08$). Interaction was not significant. After the omnibus testing, a Tukey post-hoc comparison showed

that there was one primary difference across the audio scheme. The significant difference was between the BothCont and BothThresh audio conditions for the single-UAV scenario (p=0.02). There was not a significant difference between any of the other points.

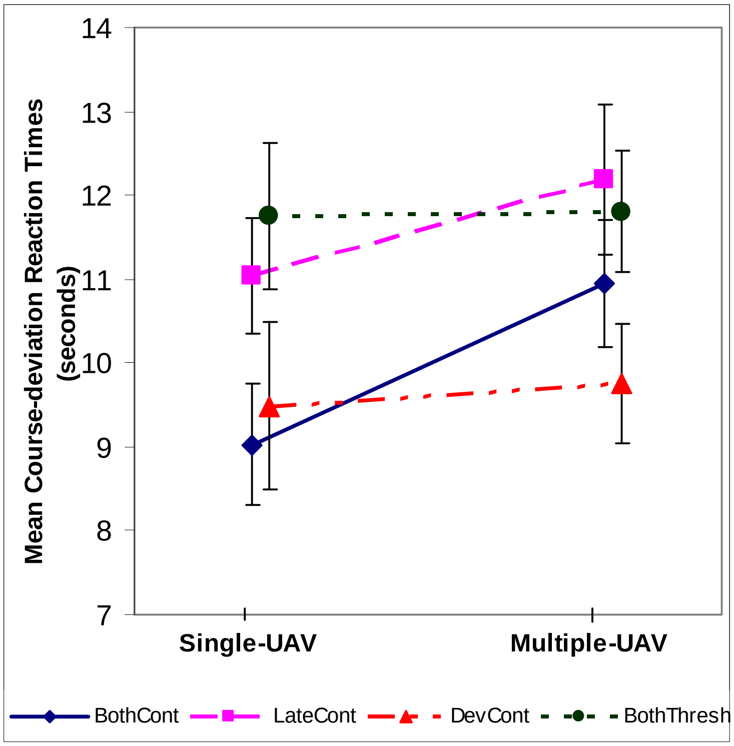


Figure 5-1: Course-deviation Reaction Times Treatment Means Plot.

In Figure 5-1 there was an apparent division in the data based on which audio alert was present for the course-deviation. As part of the post-hoc analysis based on the data clustering in Figure 5-1, with the BothCont and DevCont appearing in one group and the LateCont and BothThresh in another group, the model was reconfigured as a 2x2 fixed factor repeated measures model with audio scheme and scenario as the independent variables, respectively (Table 5-1). Instead of the four audio conditions, the factor levels were collapsed into two levels: those participants exposed to the continuous oscillating course-deviation alert (participants in the BothCont or DevCont audio conditions) and those exposed to the threshold course-deviation alert (participants in the LateCont and BothThresh audio conditions). The audio scheme

remained a between-subjects factor, while the scenario remained a repeated within-subjects factor.

Table 5-1: Post Hoc Experimental Conditions.

		Scenario (Repeated)	
		Single-UAV	**Multiple-UAV**
Audio Scheme (Between)	**Continuous Oscillating Course-deviation Alert (BothCont or DevCont)**	Participants 1-20	Participants 1-20
	Threshold Course-deviation Alert (LateCont or BothThresh)	Participants 21-39	Participants 21-39

As seen in Figure 5-2, the analysis confirms that the participants with the continuous oscillating alert condition performed significantly better than those with the threshold course-deviation alert condition ($F(1,37) = 8.874$, $p=.01$).

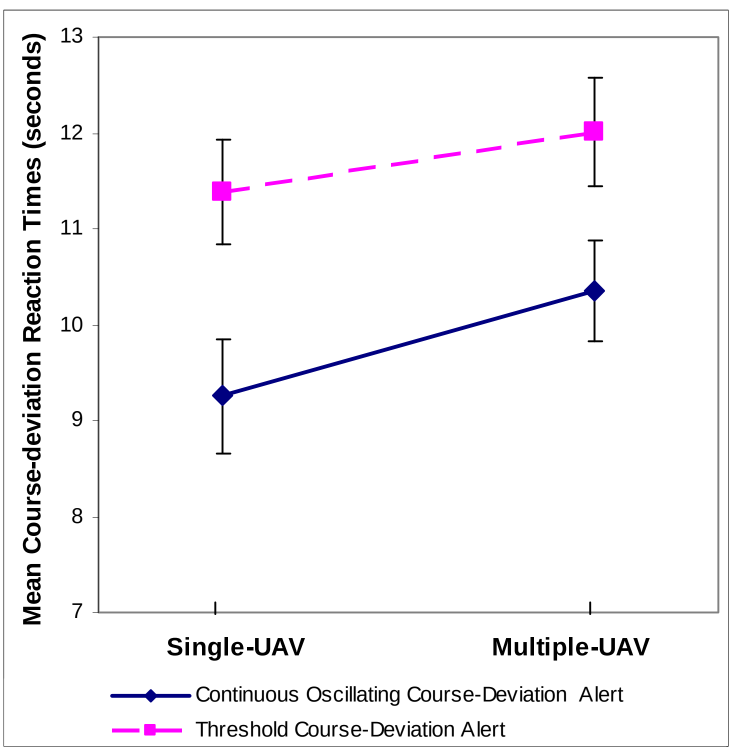


Figure 5-2: Post Hoc Analysis Course-deviation Reaction Times Treatment Means Plot.

5.3. Late-arrival Errors of Omission

All 39 participants responded to all of the 4 late-arrivals presented to each of them, thus there were no late-arrival errors of omission.

5.4. Late-arrival Reaction Times

The original late-arrival reaction times were not normally distributed, thus a natural log transformation was performed. The omnibus results showed a significant difference in the performance of participants between the four audio conditions ($F(3,35)=3.345$, $p=.03$) and a significant difference due to the scenario ($F(1,35)=20.737$, $p<.001$). Interaction was not significant.

As seen in Figure 5-3, there was an apparent split in the data. A post-hoc Tukey comparison revealed there was a significant or marginally significant difference between the data for the DevCont audio condition and the other three audio conditions: BothThresh audio condition ($p=.05$), LateCont audio condition ($p=.08$), and BothCont audio condition ($p=.07$). These post-hoc comparisons confirmed the apparent differences within the treatment means plot in Figure 5-3.

5.5. Workload

To measure workload, the performance on a secondary task was monitored, and scores for subjective workload were recorded. These are detailed in the following sections.

5.5.1. Secondary Task Assessment

For the number of missed radio calls, there was no significant difference between the audio conditions or across the scenarios. According to this secondary workload

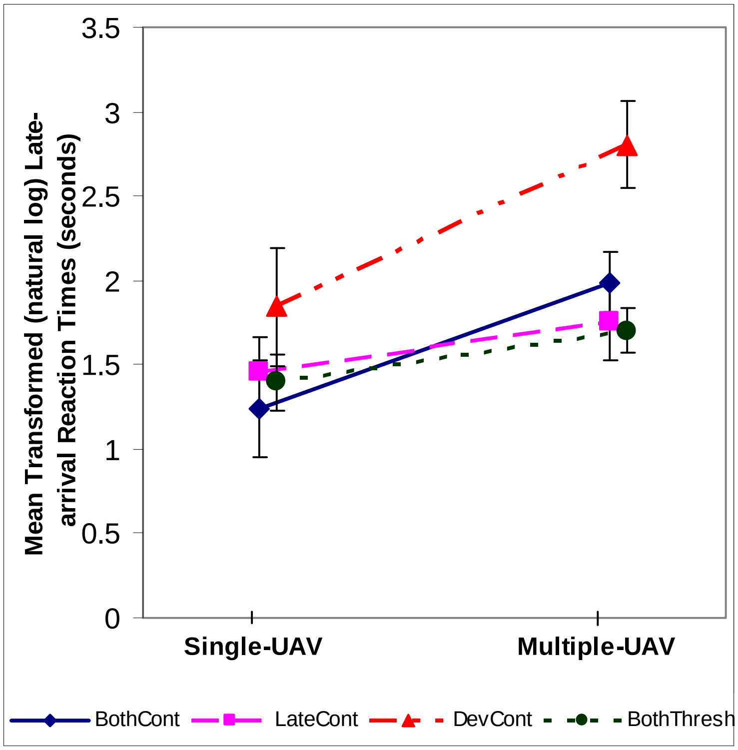


Figure 5-3: Transformed (Natural Log) Late-arrival Reaction Times Treatment Means Plot.

measurement, the participants were equally saturated, regardless of their assigned audio condition or whether they supervised a single or multiple UAVs. This was not a surprise; as discussed before and illustrated in Appendix B, the scenarios were designed with an equal number of tasks.

5.5.2. Subjective Assessment

Similar to the secondary workload measurement, the subjective measurement of the NASA TLX scores was not significantly different across audio conditions or scenarios. The non-significant results across the scenario also were not a surprise, because as illustrated in Appendix B, the single-UAV and multiple-UAV scenarios were designed to have the same number and placement of events. In the multiple-UAV scenario, the number of events and same point in time of the events was just split over four UAVs instead of all being on one UAV's flight path.

5.6. Post-Experiment Subjective Responses

Subjective responses regarding the usefulness of the audio cues, whether discrete or continuous, were overwhelmingly positive. In reviewing the participants' comments, some valuable insights were gained.

The overarching feeling toward the discrete threshold alerts was that while they were better than nothing, the discrete threshold alerts could have been improved. Many felt that these audio alerts were nice to have as they "made [the participant] pay attention" and were "a good back-up for the visual cue." The majority commented the audio alerts worked well in conjunction with the visual display to better enhance their awareness. One participant reported the audio alert "was especially helpful because noticing course-deviations visually was difficult."

A key concern raised about the threshold audio alerts was that the alerts were "hard to distinguish from background noise." The feeling was that the beeps blended into the background too easily. Threshold audio alerts were masked by things such as the general radio chatter or other alerts in the mission such as the beep that alerted the operator of new threats to avoid. One reported he found the threshold audio alert to be "too short and too discrete to call my attention. I usually noticed the late-arrivals visually." Others offered possible solutions. One said the audio alert "should be more annoying and should last longer." A common feeling was that if the audio alert was "longer and more prominent," the audio would be more effective as a supplemental tool to the visual alert. In fact, over half of the participants exposed to one of the discrete alerts asked for alerts with "more than just a simple beep" and wished for a more repetitive audio alert that would "last," so operators would have to address the alert.

Another concern raised in the threshold audio alert feedback was that the audio alerts were "difficult to use effectively with four UAVs." Some suggested, "It might

have been more helpful if it referred to the selected UAV." The results of this research support this observation. Participants needed audio support that would point them to the problem UAV, not just the fact that there was a problem with one of the UAVs.

The continuous audio alerts were generally appreciated as situational enhancers and attention managers, but some felt the continuous audio was potentially fatiguing. Although generally positive, participants did report the continuous modulated late-arrival alert "focused attention to late UAVs." Like the discrete threshold alerts, continuous audio was "audio backup" to the visual display and "alerted [participants] to the impending late-arrivals more quickly." With continuous audio, participants learned to use the continuous nature to supplement their regular visual scan, with one recounting, "I mostly looked at the left screen" and "the audio was the cue to look at the right screen." Though one reported that the continuous modulated late-arrival alert "helped with many UAVs" and another that it was a "good alert of a late-arrival," participants found it difficult to distinguish the priority of the target based on the audio alone.

While the modulated late-arrival alert was touted as an enhancement tool, it was noted by participants that the tones "provoked a stress response so that [the participant] felt more anxious." An Air Force Predator pilot noted that the modulated late-arrival alert, "while effective at alerting to issues, was extremely annoying," and he "would not subject [himself] to that background noise for hours at a time day after day."

Similar to the modulated late-arrival alert, the continuous oscillating course-deviation alert was lauded as "useful as a backup secondary cue." A negative comment about this continuous audio alert was that the audio alert could "contribute greatly to fatigue" over a long mission. Ten percent of the participants exposed to the continuous oscillating course-deviation suggested that this additional alert be left off throughout the bulk of the mission and only have the additional alert on during particular parts of the mission. This way the effectiveness of the tool could be used when the operator

needed an additional cue. At the same time, operators could be spared the annoyance of continuous audio input over a long duration mission, when they were not continually at a peak stress and work level.

Interestingly, all of the negative comments regarding the oscillating course-deviation alert came from the participants who were exposed to both the oscillating course-deviation alert and the modulated late-arrival alert (BothCont), instead of the oscillating course-deviation alert and the threshold late-arrival alert (DevCont). Twenty percent of those exposed to both were annoyed by the oscillating alert. Regardless, the majority felt the continuous audio alerts helped, but some time may be needed for operators to get used to them. As one operator stated, "Effective as they were, I just couldn't remember which was which."

5.7. Summary of Experimental Findings

Key findings of the data analysis were found in the post-hoc analyses discussed previously in this section. When the course-deviation reaction times were collapsed, those with the continuous oscillating alert condition were shown to have performed significantly better than those with the threshold course-deviation alert condition. Further, though the count of error of omissions for the course-deviations was not significant, it should be noted that almost half of all of the missed course-deviations occurred under the LateCont (comprised of threshold course-deviation and modulated late-arrival alerts) condition.

Another key finding was that for the late-arrival reaction times, the only condition that had a significant difference in performance from the other conditions was DevCont (comprised of oscillating course-deviation and threshold late-arrival alerts). The DevCont condition was shown to have significantly poorer performance than the three other audio conditions: BothCont (comprised of oscillating course-deviation and

modulated late-arrival alerts), LateCont (comprised of threshold course-deviation and modulated late-arrival alerts), and BothThresh (comprised of threshold course-deviation and threshold late-arrival alerts).

The subjective feedback results showed an overall preference for audio aids to supplement visual events, but there was annoyance reported for some of the continuous audio presentations. Many felt it would be fatiguing to run this form of audio continually throughout the long missions that some UAV operators supervise. Overall though, there was a request for more than a discrete, single beep alert.

6. Discussion

This chapter discusses the findings of the results presented in Chapter 5, *Results*. The discussion that follows presents these findings in relation to multiple resource theory, mapping of audio alerts, change blindness, and masking. It then closes with an explanation of the causes of the workload results.

6.1. Multiple Resource Theory

The anesthesiology studies discussed in Chapter 2 showed that sonifications successfully supplemented the visual modality (Watson & Sanderson, 2004). They did not replace the visual representation on the screen, but they enhanced the visual display. Similarly, within this experiment, as operators were performing tasks or even monitoring the course-deviation visually, operators relied on the aural channel to correct course-deviations quickly, which was reported in their post-test subjective feedback. This illustrates that participants were integrating the audio input to confirm and guide their visual scan to more readily identify problems.

The multiple-UAV scenario's reaction times were expected to be longer than the single-UAV scenario's; however, there appeared to be almost no differences in course-deviation reaction times between the single-UAV and multiple-UAV scenarios when the discrete threshold course-deviation audio alert was used. In comparison, the scenarios using the continuous oscillating course-deviation audio alert showed the expected trend of the multiple-UAV scenario reaction times being longer than the single-UAV scenario. This difference, between the discrete and continuous audio conditions, is likely a result of the fact that in the discrete audio condition, operators had already determined the problem visually and then waited for aural confirmation before addressing the problem. Conversely, in the continuous audio condition, the

audio first and more readily alerted the operator that there was a problem. The operator then addressed the problem by visually determining the UAV that the problem had occurred on, causing the longer reaction time for the multiple-UAV scenarios.

The continuous audio provided constant auditory input that participants relied upon to more quickly confirm their interpretation of the visual displays. Those exposed to the discrete audio had to wait until the threshold at which the audio was programmed to alert operators was met, before receiving any auditory confirmation of what they may have already perceived visually. The results of this experiment, for the course deviation reaction times, illustrate that operators had the resources to integrate the continuous audio with their visual perception, allowing them to out-perform those with the discrete audio. Thus, continuous audio better utilized the audio channel's pool of resources.

6.2. Mapping Audio Alerts to Intuitive Triggers

While this experiment showed the continuous audio helped in monitoring course deviations, it also demonstrated a case where continuous audio did not aid an operator in a supervisory role. For the late-arrival reaction times, there was no significant benefit gained by having a continuous audio alert rather than a discrete audio alert for late arrivals. The primary reason there was no performance enhancement with the continuous modulated late-arrival alert was that the late-arrivals were discrete events (a UAV was either late or not late). In relation to discrete audio, the continuous audio did not provide any extra, useful information in the late arrival condition. The audio represented one of four discrete states, rather than a continuous parameter, so it could not convey progression towards a new state, and thus the benefit of continuous audio was not fully exploited.

Conversely, the positive results of the continuous oscillating course-deviation alert were attributable to its intuitive mapping to the continually changing state of the UAV course deviation. As the UAV moved off course, the continuous audio progressively changed, and the participant was then given useful information in the sonification that allowed him to choose his own threshold for course deviations, as discussed above in the multiple resource theory discussion.

6.3. Change Blindness

In Chapter 2, *Background,* the point was raised that some forms of audio have been shown to help mitigate visual change blindness that may result from relying on only a visual presentation (Nehme & Cummings, 2006). Because there was no baseline condition, with only visual displays and no audio alerts, there is no empirical evidence that the discrete or continuous audio displays helped mitigate visual change blindness. It is noteworthy, however, that no late-arrivals and an insignificant number of course-deviations were missed by all the participants. The indication is that the combination of the visual and audio displays did, in fact, alert the participants to problem situations.

In terms of error rates in responding to both course-deviation and late-arrival events, only a very small percentage of course-deviation alerts were missed, and all of the late-arrivals were recognized by the participants. This slight difference was most likely caused by the visual alert representation in that the late-arrival visual alert was easily seen by the physical displacement and color change of the target icon (Figure 3-3). In contrast, whether a UAV was truly off course was more visually ambiguous, as is seen in Figure 3-5. This was exacerbated by the simulation, which caused the UAV to automatically resume its correct course if a participant did not recognize and correct an off-course error within thirty seconds. This illustrates the importance of dual coding

alerts on the visual and aural channels, which is one way to combat change blindness and was generally effective in this experiment.

6.4. Masking

The subjective feedback of the participants suggested that they felt the discrete threshold alerts were masked by other clutter and noise in the radio chatter, which is why the discrete threshold alerts may not have performed as well as the continuous ones. In general, the results showed that almost half of the missed course-deviations occurred in the audio condition, where the continuous modulated late-arrival audio alert was present in a scenario with the discrete threshold course-deviation audio alert. Further, the results showed that late-arrival recognition was no different across conditions, except for a significant decrease in performance when the continuous oscillating course-deviation alert was present along with the discrete threshold late-arrival audio alert. Both of these statistical results are examples of how masking can result in degraded performance. Therefore, a continuous audio alert should be integrated with the other alerts so that masking of less prominent discrete or even continuous alerts does not occur.

6.5. Workload

The workload measurements (subjective responses and secondary task performance) showed no significant difference between the single-UAV and multiple-UAV scenarios. The operators reportedly perceived no difference in the workload, which was not a surprise. As discussed before and presented in Appendix B, the two scenarios were designed with the same number and types of events. The only difference was that for the multiple-UAV scenario, the events were separated over four

UAVs instead of one UAV. The intent was to provide the same number of tasks, and thus the same amount of work, in each scenario. Because there was an identical set of events for much of the experiment, participants likely recognized no difference in their efforts between the two scenarios. This was supported by the similar performance on the secondary task for the single-UAV and multiple-UAV scenarios.

Although the workload measurements were not significant, the performance metrics were different between the scenarios. The late-arrival reaction times were significantly different, and the course-deviation reaction times were marginally different. In both cases, there were shorter reaction times for the single-UAV scenario than the multiple-UAV scenario. This performance difference is likely the result of participants having to divide their attention while monitoring four UAVs for the multiple-UAV scenario. The impact of divided attention for multiple UAV control will be discussed further in the findings section of Chapter 7, *Conclusion*.

7. Conclusion

In this concluding chapter, the primary research questions are answered, followed by a discussion of workarounds to potential integration issues and areas for future research.

7.1. Findings

The primary questions addressed through this research are as follows:

1. When compared with discrete audio, does continuous audio better aid human supervision of UAV operations?
2. Is the effectiveness of the discrete or continuous audio support dependent on operator workload?

7.1.1. Value Added by Continuous Audio

From the experiment results for the single and multiple-UAV scenarios, it appears that the continuous oscillating course-deviation audio alert helped participants respond more quickly to the task of recovering from UAV course-deviations. The continuous modulated late-arrival audio alert, in contrast, did not help or hinder the participants in responding to late-arrivals, primarily due to a confound in alert mapping.

These results highlight the importance of context in alert design. When the continuous oscillating course-deviation audio alert was used with the discrete threshold late-arrival audio alert, reaction times to addressing late-arrivals were significantly worse than all other cases, due to masking. In contrast, when used with the continuous

modulated late-arrival audio alert, the late-arrival reaction times did not suffer, and the course-deviation reaction times improved.

Thus, continuous audio alerts helped in UAV control, but they must be added in light of all the other audio input occurring in the display. Caution must be taken so that the added benefit of a continuous audio alert is not lost because of a lack of proper system integration. Further, continuous audio must only be applied in cases where it maps to the occurrences of the event that is being monitored. If it is a discrete event, like late-arrivals, there may not be a gain in using continuous audio in place of discrete audio.

7.1.2. The Impact of Workload

The results indicate a decrease in performance when supervising multiple UAVs instead of a single UAV, regardless of the audio condition. The performance degradation in the multiple-UAV condition is not a surprise. Task load stress means that even with a constant signal rate, performance will decline if more information inflow must be used (Conrad, 1985). This means that even with the same number of tasks, if the tasks are distributed over multiple vehicles, the performance will decrease. The effects of load stress have been illustrated in air traffic control (Cummings & Tsonis, 2005) and UAV studies (Cummings & Mitchell, 2008; Cummings, Nehme, & Crandall, 2007; Dixon et al., 2005). Given the results of previous research, there is no reason to assume the results of this study would have been any different. However, the use of continuous audio displays was meant to alleviate some of this increased workload, and participants recognized this in the subjective responses, noting that though the audio alerts were "very helpful" when focusing on other tasks, it was "harder to comprehend with four UAVs than one."

On the whole, though, participants exposed to continuous audio outperformed participants exposed to discrete audio in both the single-UAV and multiple-UAV

scenarios. Previous research controlling two UAVs showed that an audio alert improves performance over a baseline condition of no audio but that generally, performance degrades when the number of UAVs under control increases (Dixon et al., 2005). The results of this thesis mirror this previous research, except that it was shown that continuous audio, when used appropriately, can actually mitigate the negative impacts of increased workload due to increased numbers of UAVs under control.

The conclusion to these research questions is that with correct application, continuous audio is more helpful than discrete audio in supporting the supervision of multiple tasks over multiple vehicles. While continuous audio may be a performance enhancer, it is also important to assess the research and development, acquisition, and maintenance costs associated with fielding this new headphone technology. Quantification of these various factors will determine whether such technology should ultimately be employed, which will be discussed next.

7.2. Integration Issues

A shortcoming in the use of headphones for the presentation of the continuous audio is the isolation of the operator from outside communication (Tannen, 1998). In operational integration with military personnel, operators will often only wear one half of the headset because wearing the headset on both ears isolates them from inter-team interaction. It is important to make sure that any integration of a headset does not interfere with critical work environment constraints, especially those in a team setting.

Furthermore, though continuous audio can promote objective performance, some participants in the experiment noted an annoyance with long term exposure to these forms of continuous audio. One solution in integration is to limit exposure to the audio and only use it when needed. For example, rather than play continuous audio throughout an entire four-hour mission, the continuous audio tool could be active only

during the portion of the mission when workload is heavy, or when one of the peripheral tasks reaches a cautionary state that may require the human operator's intervention. Thus, this kind of adaptive display could either add or remove audio aids as required by the workload situation.

7.3. Cost-Benefit Analysis

While the results show that continuous audio displays improved operators' performance, the question is to what extent? In addition, in comparison to this benefit, what is the cost to the DOD to actually acquire these displays?

To consider quantitative benefits of the continuous audio displays, the reaction times to course-deviations and late-arrivals are reviewed. The results show that with the continuous audio, participants were on average 2 seconds or 6 seconds faster at responding to course-deviations or late-arrivals, respectively, than the participants with the discrete audio display. Thus, these experimental results show a performance enhancement of a 31 percent decrease in reaction times for monitoring tasks with the aid of continuous audio displays instead of the aid of discrete audio displays. In aviation this time interval can be critical, particularly in UAS operations where operators deal with time lags in the control of remote vehicles. Linking continuous audio to support operators in monitoring time critical events could be very beneficial.

In terms of the actual hardware, the HDiSP is still a new technology and is the only headset of its kind. The HDiSP used in this experiment was a prototype version provided by Sensimetrics. To date, Sensimetrics is only providing HDiSP for custom orders. Two HDiSPs, along with the software, have been sold at a cost of 3,750 dollars per headset (T. E. von Wiegand, personal communication, April 2, 2008). Sensimetrics estimates that if they were mass producing the HDiSP, the headset would sell between 1,000 and 2,000 dollars per headset (T. E. von Wiegand, personal communication, April

2, 2008). In contrast, the best aviation headsets cost about 300 dollars (SkyGeek, 2008). Overall the price increase of purchasing the HDiSP instead of aviation headsets would be about 1,200 dollars (400 percent), if the HDiSP was mass produced at 1,500 dollars per headset.

Rough performance and cost increases can be calculated, but these numbers mean nothing unless placed in some context. For instance, in the motivation section of Chapter 1, *Introduction*, the statistic was cited that over the next 8 years, 15.7 billion dollars will be spent on UAVs in the United States, yielding 11,000 UAVs in operation (Tsach et al., 2007). Equipping each UAV with an HDiSP for single operator supervision would result in a cost of 13 million dollars, which is less than 0.1 percent of all the money projected to be spent on UAVs in the United States in the next 8 years.

While there is a cost to integrating a new continuous audio system, there are also research and development costs for continuous audio displays and HDiSP technology. Further, there would likely be additional maintenance costs for the HDiSP, which is a more complex hardware device that may not be as sturdy in field conditions as older, more robust aviation headphones. Dependent upon implementation, if there were significant maintenance issues, there would be social costs as well. Operators might lose trust or grow frustrated with the constant maintenance and then stop using the device.

The results of the experiment in this thesis illustrate continuous audio displays provide a performance enhancement. When compared with participants' performance with discrete audio displays, the continuous audio displays are shown to decrease reaction times by 31 percent. An initial cost benefit analysis shows that the cost of implementing such a device is minimal, but future research is needed to do a full analysis of economic, operational, and social costs of implementing these new audio displays into UAS interfaces.

7.4. Limitations and Future Work

- A limitation of this research is that it assumes a certain level of autonomy in the unmanned vehicles, such as the vehicles flying themselves from waypoint to waypoint, with the operator performing a distinct payload mission. The research presented here focuses on the human operator acting in a higher supervisory role.
- The tasks represented by the continuous audio alerts were not primary tasks, but secondary tasks that required occasional operator input. The results may have been different had the continuous audio alerts been linked directly to the primary task.
- Within the MAUVE simulator, there is a rapid onset of change for the course-deviation and late-arrival events. Future research could be done on a simulator that allows for a more gradual onset of change to further explore how the rate of increase for the audio intensity affects the speed and confidence of response by the participants. In particular, how the onset of change for the continuous audio helps alert the participant to the problem is an area of future research.
- While continuous audio alerts have been proven beneficial in comparison to discrete audio alerts, further research could be completed to investigate the different patterns of sonifications to see which is best for helping operators supervise multiple tasks on multiple vehicles.
- Another future study could compare the benefits of continuous audio alerts with spatial audio and test the integration of continuous audio into a spatial audio presentation. The point of this future study would be to test the value added when continuous audio is used with or in addition to spatial audio.
- These results suggest that perhaps a better implementation of continuous audio alerts is to use them only during high workload situations, so as to minimize any

annoyance factor, while maximizing the objective benefits of the tool. Future research could test ways to build the sonifications into adaptive audio displays that change the amount and type of audio output based on the workload presented by the system to the operator.

- Another extension of this research would be investigating how haptic cueing, either as a replacement or an addition to the continuous audio alerts, would affect performance.

Appendix A: Audio Alert Guidelines

According to Deatherage (1972) and Sanders and McCormick (1993), the following guidelines should be considered in designing to meet the physical parameters of the human ear and hearing:

- Use sounds in the 200 to 5000Hz range, in particular the 500 to 3000Hz because this middle range is the most sensitive region for human hearing.
- To avoid masking in noise, use signal frequencies different from the noises' most intense frequencies.
- To capture attention, use modulated sounds of intermittent beeps repeating one to eight beeps per second or warbling sounds that vary between 1 to 3 times per second, because these sounds rarely occur naturally and will capture operator attention.
- If representing different conditions, different warning signals should be discriminable from each other, and moderate-intensity signals should be used.

Appendix B: Scenario Events

Appendix B shows that the single-UAV and multiple-UAV scenarios were designed with the same number of events. The only difference was that the multiple-UAV scenario has the events divided over four UAVs, while the single-UAV scenario has them all occurring with one UAV. The timeline of events for the two scenarios (Figure B-1) illustrates this.

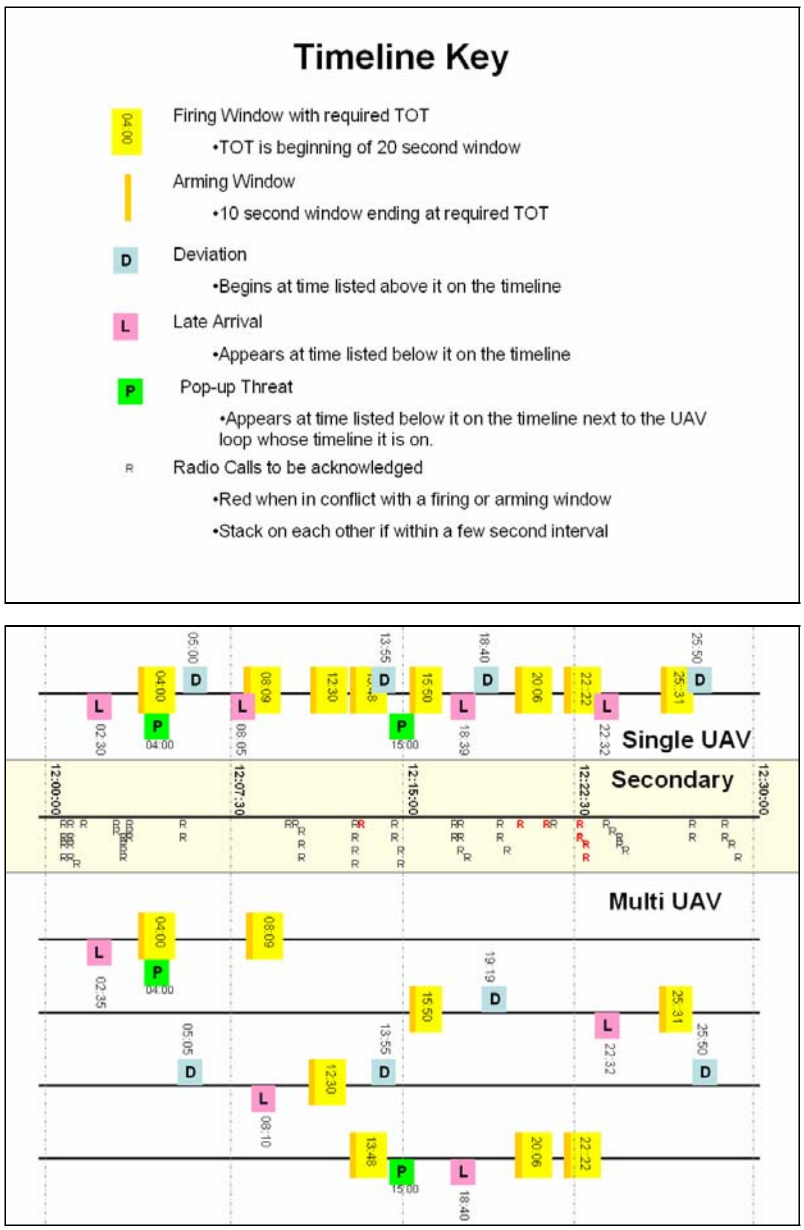
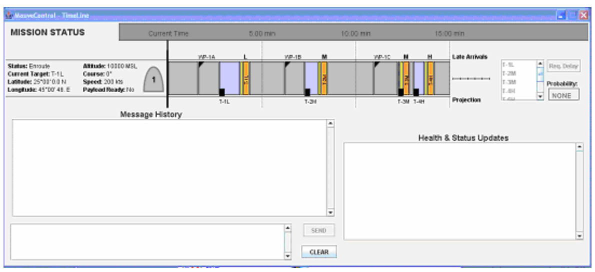
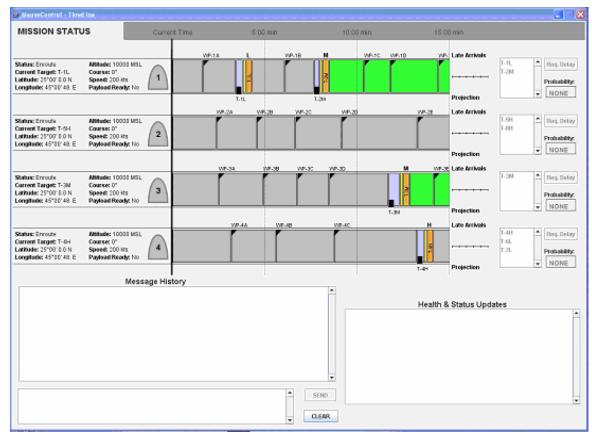
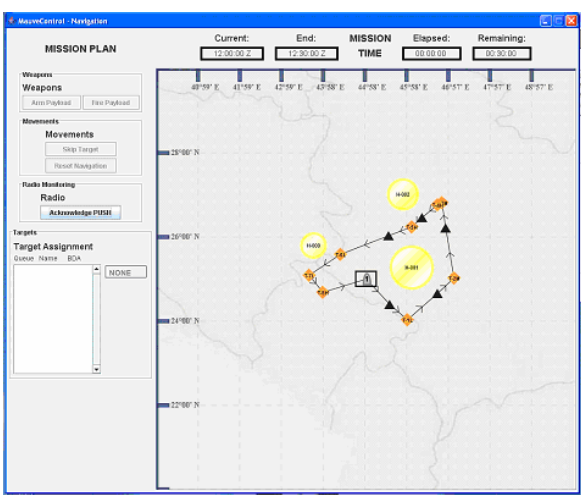
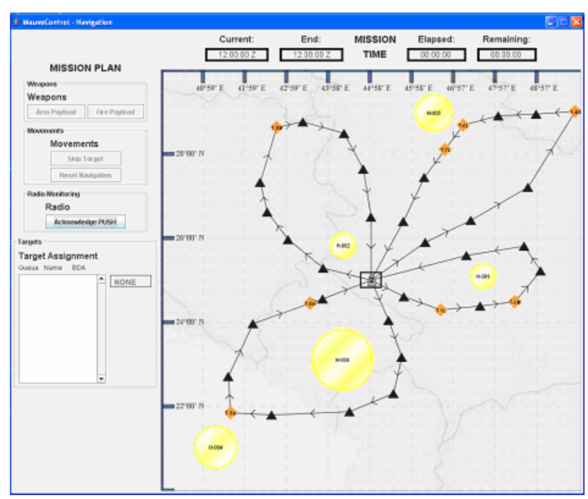


Figure B-1: Major Events of Single-UAV and Multiple-UAV Test Scenarios.

Table B-1 shows side-by-side images of the timeline display and map display for the single-UAV and multiple-UAV scenarios. Again, as with the timeline in Figure B-1, these displays show that in both scenarios the operator has the same number of tasks to complete, and the only difference between the two scenarios is that for the multiple scenario, the tasks are divided over four UAVs instead of just one UAV.

Table B-1: Comparison of Single-UAV and Multiple-UAV Scenarios.

	Single-UAV Scenario	Multiple-UAV Scenario
Timeline Display		
Map Display		

Appendix C: Participant Consent Form

**CONSENT TO PARTICIPATE IN
NON-BIOMEDICAL RESEARCH**

Developing Decision Support for Supervisory Control of Multiple Unmanned Vehicles

You are asked to participate in a research study conducted by Professor Mary Cummings Ph.D, from the Aeronautics and Astronautics Department at the Massachusetts Institute of Technology (M.I.T.). You were selected as a possible participant in this study because the expected population this research will influence is expected to contain men and women between the ages of 18 and 50 with an interest in using computers. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

The study is designed to evaluate how decision support tools or recommendations, both audio and visual, assist an operator supervising multiple simultaneous dynamic tasks, and how decision support assistance and effectiveness changes as workload increases. In measuring the effectiveness of decision support, an operator's performance and situation awareness are used as metrics. Situation awareness is generally defined as the perception of the elements in the environment, the comprehension of the current situation, and the projection of future status of the related system.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

- Attend a training and practice session to learn a video game-like software program that will have you supervising and interacting with multiple unmanned aerial vehicles (estimated time 0.75 hours).
- Practice on the program will be performed until an adequate level of performance is achieved, which will be determined by your demonstrating basic proficiency in monitoring the vehicles, redirecting them as necessary, executing commands such as firing and arming of payload at appropriate times, using decision support visualizations and/or recommendations to mitigate timeline problems, and responding to radio calls by clicking an acknowledge button on the software interface (estimated time 0.75 hours).

- Execute two thirty minute trials consisting of the same tasks as above (1 hour)
- Attend a debriefing to determine your subjective responses and opinion of the software (10 minutes).
- Testing will take place in MIT building 37, room 301.
- Total time: 2-3 hours, depending on skill level.

- **POTENTIAL RISKS AND DISCOMFORTS**

There are no anticipated physical or psychological risks in this study.

- **POTENTIAL BENEFITS**

While there is no immediate foreseeable benefit to you as a participant in this study, your efforts will provide critical insight into the human cognitive capabilities and limitations for people who are expected to supervise multiple complex tasks at once, and how decision support tools can support their task management.

- **PAYMENT FOR PARTICIPATION**

You will be paid $10/hr to participate in this study which will be paid upon completion of your debrief. Should you elect to withdraw in the middle of the study, you will be compensated for the hours you spent in the study.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You will be assigned a subject number which will be used on all related documents to include databases, summaries of results, etc. Only one master list of subject names and numbers will exist that will remain only in the custody of Professor Cummings.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact the Principal Investigator, Mary L. Cummings, at (617) 252-1512, e-mail, missyc@mit.edu, and her address is 77 Massachusetts Avenue, Room 33-305, Cambridge, MA 02139. The student investigators are Hudson D. Graham (719-238-1713, email: hgraham@mit.edu), and Amy Brzezinski (617-276-6708, amybrz@MIT.EDU).

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

"In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of

the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253-2822."

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

______________________________________ ______________
Signature of Subject Date

SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

______________________________________ ______________
Signature of Investigator Date

Appendix D: Demographics Survey

MAUVE-MITUS Demographic Survey

1. **Age:** ____________________

2. **Gender:** □ Male □ Female

3. **Occupation:** ___________________

   If student:

   a. *Class Standing:* □ Undergraduate □ Graduate
   b. *Major:* ____________________

   If currently or formerly part of any country's armed forces:

   a. *Country/State:* ____________________
   b. *Status:* □ Active Duty □ Reserve □ Retired
   c. *Service:* □ Army □ Navy □ Air Force □ Other ____________________
   d. *Rank:* ____________________
   e. *Years of Service:* ____________________
   f. *Did you ever serve in high noise environments?* □ Yes □ No
   ***If yes**, please explain what the duties were, how long the shifts were, and how many times you served these shifts?*

   ____

   ____

4. **Do you have experience with remotely piloted vehicles (land, sea, air)?**
   □ Yes

   □ No

   If yes:

   a. *Vehicle type(s)/class(es):*
   ____
   b. *Number of hours:* ____________________

5. **Do you have experience with radios such as those used for communication in flying?**
   □ Yes

   □ No

   If yes:

Please explain:

____

____

6. **Have you been to a music concert in the last Month?**

□ Yes

□ No

If yes:

a. *Concert type:*____
b. *When:* ____________________

7. **Do you have any hearing loss?**

□ Yes

□ No

If yes:

Please explain:

____

____

8. **How often do you play video games?**

□ Never

□ Less than 1 hour per week

□ Between 1 and 4 hours per week

□ Between 1 and 2 hours per day

□ More than 2 hours per day

9. **Are you color blind?**

□ Yes

□ No

If yes:

Which type of color blindness (if known): ____

Appendix E: MAUVE-MITUS Tutorial

Spring 2007

Multi-Aerial Unmanned Vehicle Experiment (MAUVE) TUTORIAL

Hudson Graham – MIT Humans and Automation Lab

Introduction

Welcome!

This tutorial is designed to give you some background on the Multi-Aerial Unmanned Vehicle Experiment (MAUVE) interface before you arrive on testing day. Please take the time to look over the following slides and come prepared with questions. Before testing you will be thoroughly trained on the actual interface, but being exposed to it beforehand will be invaluable in speeding up this process.

Thank you in advance for your participation!

Experiment Overview

In this experiment, you are an unmanned aerial vehicle (UAV) operator that is responsible for supervising 1 to 4 UAVs collectively tasked with destroying a set of time-sensitive targets in a suppression of enemy air defenses mission. The area contains enemy threats capable of firing on your UAVs.

The UAVs are highly autonomous, and therefore only require high level mission execution from you. The UAVs launch with a pre-determined mission plan, so initial target assignments and routes have already been completed for you. Your job will be to monitor their progress, re-plan aspects of the mission in reaction to unexpected events, and in some cases manually execute mission critical actions such as arming and firing of payloads.

The interface we have developed for this experiment is called the Multi-Aerial Unmanned Vehicle Experiment (MAUVE) and will be referred to by this name from here out.

Objectives

Your primary objective in this mission is:

To make sure the UAV(s) maximize the number of targets engaged as well as arriving back to the base safely.

Supervision of the UAVs can be broken down into the following prioritized sub-tasks, from highest priority to lowest:

1. Return to base (RTB) within the time limit for the mission (this limit will be clearly marked).
2. Comply with recovery rules for course deviations.
3. Comply with recovery rules for target late arrivals.
4. Destroy all targets before their time on target (TOT) window ends.
5. Avoid taking damage from enemies by avoiding all threat areas.
6. Acknowledge all "Push" radio calls.

These sets of objectives will often conflict with one another. In these cases, you must perform the actions that have the highest priority first.

Your performance will be judged based on how well you follow the above priorities.

Audio Alerts

To help you meet your objectives you will receive auditory signals for both course deviations and late arrivals. Both are induced by unanticipated high winds along the planned flight path.

Course deviations are when a UAV is blown off of the planned path. It is significantly deviated when you visually see that the UAV has left the course line. Deviations may occur over targets as well.

Late arrivals are when the UAV has hit stronger than anticipated head winds and slows down. As a result it will now be late to the next target.

Your test proctor will provide further training as to what these auditory signals sound like during the test day training.

Other auditory sounds to be familiar with are: (Note all three are the same because all are related to a new message in your message box.)

For new messages in your message boxes

For pop-up threats

For when your UAV is being fired upon while flying through a threat area.

Color Coding

Throughout the displays you're about to see, the following color coding is used to indicate each of the 5 possible actions a UAV can perform in MAUVE:

UAV Action	Color
Enroute	Gray
Loitering	Blue
Arming Payload	Yellow
Firing Payload	Orange
Return to Base	Green

Displays – Overview

During the experiment, you will see two side-by-side displays that contain the following major elements:

- **Left Display**
  - **Mission Time**
  - **Map Display**
  - **Mission Execution**
- **Right Display**
  - **Unmanned Aerial Vehicle (UAV) Status**
  - **Decision Support**
  - **Chat Box**
  - **UAV Health & Status Updates**

The following slides will show these displays in detail and explain how to use them properly.

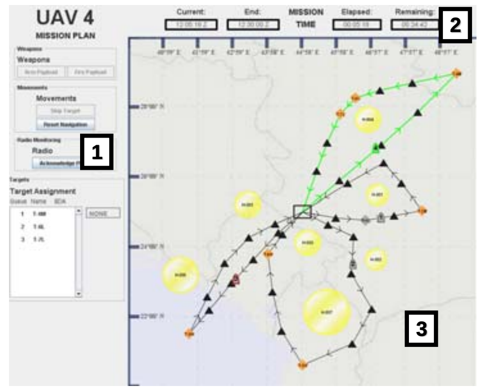
Left Display – Overview

The three major screen elements on the left display are:

1
Mission Execution

2
Mission Time

3
Map Display



Right Display – Overview

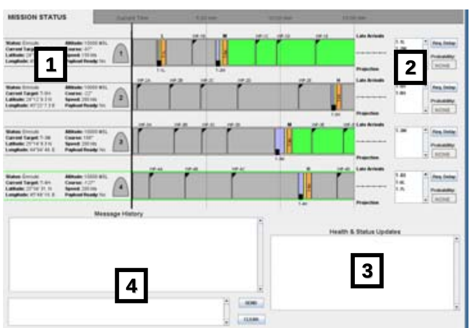
The four major screen elements on the right display are:

1
UAV Status

2
Decision Support

3
UAV Health & Status Updates

4
Chat Box



Left Display – Detail

The following slides detail all of the elements contained on the left display, in this order:

- **Map Display**
- **Mission Execution**
- **Mission Time**

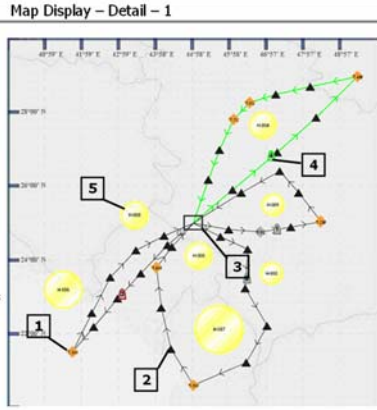
Map Display – Detail – 1

Key Map Display Elements

1. Active Target
2. Waypoint
3. Base
4. UAV
5. Threat Area

Mission Plans

- The solid black lines indicate each UAV's current mission plan
- The currently selected mission plan is highlighted green
- One UAV will always be highlighted with a red border. This UAV has the greatest course deviation. It corresponds to the course deviation auditory signal you will be receiving.



Map Display – Detail – 2

Naming Conventions

- ***UAVs***
  - **Numbered 1-4**
- ***Targets***
  - **T-XXP where XX = target number and P = priority**
  - **Priority may be High (H), Medium (M), or Low (L)**
  - **Examples:**
    - **T-1H – Target 1 a high priority target**
    - **T-12M – Target 12 a medium priority target**
    - **T-23L – Target 23 a low priority target**
- ***Waypoints (WP)***
  - **WP-XY where X = UAV# the waypoint is associated with and Y = waypoint letter**
  - **Examples: WP-1A, WP-2C**
- ***Threats/Hazards***
  - **H-XXX where XXX = threat number**
  - **Example: H-001, H-012**

Mission Time – Detail

The mission time display element shows the following:

1. **Absolute Time**
   - **These clocks are on the left side of the "Mission Time" title**
   - **Two formats**
     - **Current Time: Current mission time**
     - **End Time: End time of the current mission**
2. **Relative Time**
   - **These clocks are on the right side of the "Mission Time" title**
   - **Two formats**
     - **Elapsed Time: How long has elapsed since the start of the scenario**
     - **Remaining Time: How long remains until the mission is over**

Example Mission Time Display Element

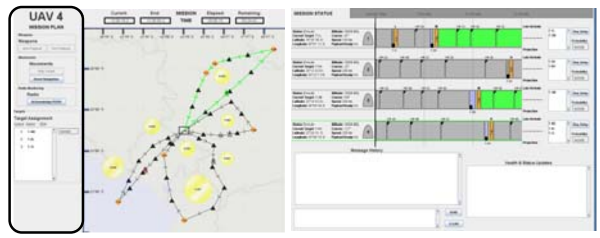
Mission Execution – Detail – 1

Each UAV has its own mission execution bar.

To bring it up on the left display, click anywhere on the desired UAV's status window on the right display OR on the UAV icon itself on the left display.

Light green highlighting around the UAV's status bar and its current mission plan on the map display tell you which UAV/route is currently selected

In the display below UAV 4 is highlighted so this is the mission execution bar on the left side of the left display.



Mission Execution – Detail – 2

Mission Execution Functions

1. **Arm Payload**
   - **This button is only enabled if the UAV is selected while directly on top of a target, and within the arming or firing windows**
2. **Fire Payload**
   - **This button is only enabled if the UAV is selected while directly on top of a target, armed, and within the firing window for that particular target**
3. **Skip Target**
   - **This button is used if you decide to skip a target because you are going to be late to it. It causes the UAV to skip the next target/waypoint and move to the next waypoint/target**

1 2 3

Mission Execution – Detail – 3

Mission Execution Functions

4. **Reset Navigation**
   - **Click anytime you have a significant course deviation and want to return to the planned course; it will return the UAV to the next plotted waypoint/target.**
   - **Causes the UAV to be inactive while resetting; you may not be able to arm or fire with that UAV when its navigation system is resetting.**
5. **Radio Monitoring**
   - **Radio chat from the Boston ground control will be playing and you must click the "Acknowledge PUSH" each time "push" is called on the radio chat. *Hint: Push calls usually come in pairs (but not always); the tower and an aircrew or vice versa.***
6. **Target Assignment Queue**
   - **You will not be using this portion of the display.**

4 5 6

Right Display – Detail

The following slides detail all of the elements contained on the right display, in this order:

- **UAV Status**
- **Health & Status Updates**
- **Decision Support**
- **Chat Box**

A Reminder of How it All Fits Together – Right Display

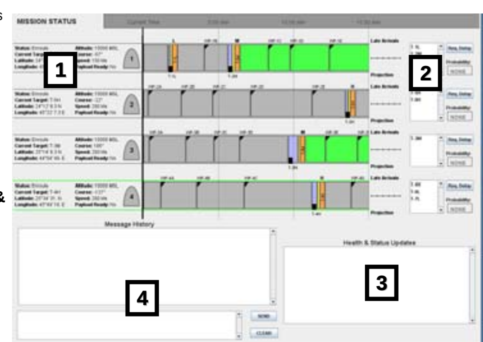
The four major screen elements on the right display are:

1
UAV Status

2
Decision Support

3
UAV Health & Status Updates

4
Chat Box



UAV Status – Detail – 1

The UAV status display shows the following real-time information for each UAV:

- Status / Current Action
  - This is written out as well as represented by the color of the UAV icon to the right
  - For example: a blue UAV would be loitering. This means it has arrived over the target but is there before the arming and firing window so is in a holding pattern waiting for these windows.
- Current Target Name
- Position in Latitude & Longitude
  - You will not need this in the scenario.
  - Given in degrees, minutes, and seconds
- Altitude
  - This is a static number that is not used in the scenario in any way

Example UAV Status Display Element

(continued on next slide)

UAV Status – Detail – 2

The UAV status display shows the following real-time information for each UAV:

- Course
  - You will not need this during the scenario.
  - 0˚ indicates due north; increases in a clockwise manner
- Speed
  - The UAVs are set to travel at a constant speed of 200 kts.
  - If there is significant head wind the UAV may slow down. This can precipitate late target arrivals
- Payload Ready
  - This reflects whether the UAV has a payload ready for the current target
  - Will say "Yes" if the UAV is armed, "No" if not

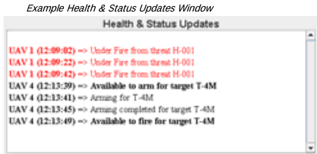
Example UAV Status Display Element

UAV Health & Status Updates – Detail

The Health & Status Updates box contains messages from specific UAVs intended to inform the operator. Messages are color coded as follows:

- Red = UAV Health messages
  - UAV is under fire from a threat
  - Again, a standard audio alert will play when you receive red messages.
- Bold Black = UAV Status messages, action required
  - UAV is available to arm or fire
- Black = UAV Status messages, no action required
  - UAV has completed arming or firing

Example Health & Status Updates Window



Decision Support – Remember the Color Coding

Color coding is an important element of the decision support, so take a look at it again!

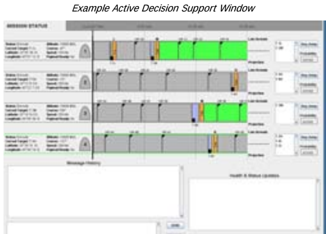
UAV Action	Color
Enroute	Gray
Loitering	Blue
Arming Payload	Yellow
Firing Payload	Orange
Return to Base	Green

Decision Support – Detail – 1

The active level of decision support contains a visual representation of what and when targets are approaching through a relative timeline and projective decision support display for each UAV.

- The arming and firing windows cannot by changed solely at the will of the the operator. i.e. Operators may request time on target (TOT) delay requests, but must get approval before the arming and firing window will be moved back (if approved).

Example Active Decision Support Window



Decision Support – Detail – 2

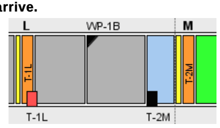
Arming and firing elements are color coded in the same way as corresponding UAV actions. For each target the following information is represented:

1. Arming Window = Yellow
   - 10 seconds long and takes approximately 3-7 seconds to arm.
   - Payload for the relevant target may be armed, but not fired during this time
   - Always occurs immediately before the firing window
2. TOT/Firing Window = Orange
   - 20 seconds long and takes approximately 3-7 seconds to fire.
   - Payload must be fired at the relevant target during this time
   - In addition to the arming window, a payload may also be armed during this time
   - Target name is printed vertically in the center of the window, priority is printed above the window.

Decision Support – Detail – 3

Mission planning information reflects when UAVs will reach important points in the scenario, such as:

1. **Waypoints/Loiterpoints/Base = Black Triangles**
   - **Names are printed above the relevant UAV's timeline**
2. **UAV Arrival at Targets = Black Rectangles**
   - **Names are printed below the relevant UAV's timeline**
   - **Note that each target name will appear twice on the timeline, once for when the UAV will arrive at that target and once at the center of that target's firing window**
3. **Late UAV Arrival = Red Rectangles**
   - **Black Rectangle turns red and moves past the target to when the UAV will arrive.**

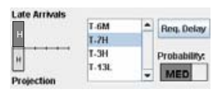


Decision Support – Detail – 4

The active level of decision support aids the user by identifying possible late target arrivals and areas of potential high workload on the timeline.

- **A late target arrival is defined as when a UAV will arrive to a target after its scheduled time on target**
- **Corrective actions for late arrivals are based on the priority of the target you are projected to be late to. For:**
  - **Low priority targets, skip them by clicking "Skip Target" on the navigation screen.**
  - **Medium priority targets, either skip them or use the decision support visualization (DSV) to possibly request a delay. Remember your priorities of wanting to hit all the targets. *See the next four slides for an explanation of how to use the DSV (shown below).***
  - **High priority targets, use the DSV and then decide whether to request a TOT delay or to skip the target by clicking "Skip Target"**

Note: The corrective actions above should only be taken when a late arrival is projected by the red rectangle on the screen and your audio.



Decision Support – Detail – 5

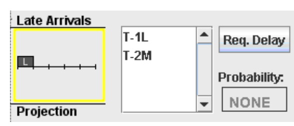
The decision support visualization (DSV) helps the user manage the schedule by showing timeline issues and projecting "what if" conditions of the effects on the timeline based upon user decisions.

- **Each UAV's DSV is uses emergent features to show problems that currently exist or that may exist if a TOT delay is given.**
- **No issues (late target arrivals) are indicated by no rectangles being displayed.**
  - **The picture below shows the DSV for when there is no late arrivals. It depicts this by having no rectangles above the line on the left side of the display in the "Late Arrival" section.**

Note: The DSV will be inactive except for when you are going to be late to a medium or high priority target.

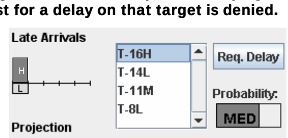
Decision Support – Detail – 6

- **Late arrivals are represented by a rectangle occurring on the DSV above the line on the left side of the display in the "Late Arrivals" section. It will also be highlighted yellow as it is below.**
  - **The target's priority is indicated within the rectangle and by the rectangle's size. The higher the priority of the target that the UAV will be late for the taller the rectangle will be.**



Decision Support – Detail – 7

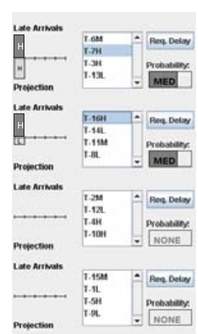
- **Below the center line is for the "what if" condition; after the user selects a target that they might request a TOT delay for it will show the projected future late arrivals for that UAV below the centerline on the left side of the display in the "Projection" section.**
  - **The example below shows that if a TOT delay request is granted for target T-16H, the UAV will then be late to a Low Priority target.**
  - **The Probability in the bottom right of this display shows the likelihood of a TOT delay being granted. The further in advance a delay is requested the higher the likelihood of it being granted. Do not request a delay again if your first request for a delay on that target is denied.**



Decision Support – Detail – 8

Each UAV possesses a DSV display to help the user understand the potential effects of decisions

- A list of all the mission targets on the timeline appears to the right of each UAV's DSV display.
- In using the display to the right for the top UAV:
  - The user is considering requesting a delay for T-7H, a high priority target. However, it shows they will now be late to another high priority target even with this delay. This is where you, as the user, will have to make a value call. Do you request a delay or skip the target by clicking "Skip Target?" Most of the time you will not want to request a delay if you know it is going to create another delay.
- In using the display to the right for the second UAV:
  - The user is considering requesting a delay for T-16H, a high priority target. This will result in the UAV being late to a low priority target. So in this case you, as the user, would want to request this delay because it means you can hit the high priority target for the trade-off of now missing a low priority target.



Chat Box – Detail

The chat box contains a time history of all *human* interactions. These interactions are color coded as follows:

- **Red = Intelligence updates**
  - **Again, a standard audio alert will play when you receive red messages.**
- **Black = Message to/from Base, no response required**
  - **Messages that inform you, but do not require a specific response**

The chat box is purely informational. It will provide you with updates, but you will not input anything in the chat box.

Example Message History Window

Conclusion

You are now ready to proceed to hands-on training with the MAUVE interface. Remember to bring any questions you have to the experimenter on testing day!

Predator B

Global Hawk

Appendix F: Post-Experiment Survey

MAUVE Post-Test Feedback

1. How did the audio cues help or hinder you in managing *late-arrivals*?

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2. How did the audio cues help or hinder you in managing *course-deviations*?

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3. How would you change the audio cues for the *late-arrivals* to have them better aid you during your mission?

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4. How would you change the audio cues for the *course-deviations* to have them better aid you during your mission?

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5. In general how would you change all the audio to help you with the control during your mission?

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6. Please express any other comments you may like to share:

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Appendix G: GLM Analysis: SPSS OUTPUT

Included in this appendix are the key SPSS outputs for the data analysis.

G.1. Course-deviation Reaction Times (for 4 audio conditions)

Met normality and homogeneity assumptions.

Table G-1: Course-deviation Reaction Times (4 audio conditions) Within-Subjects Contrasts.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	14.029	1	14.029	3.215	.082
scenario * Audio_Scheme	Linear	10.780	3	3.593	.824	.490
Error(scenario)	Linear	152.711	35	4.363		

Table G-2: Course-deviation Reaction Times (4 audio conditions) Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	8998.235	1	8998.235	1089.907	.000
Audio_Scheme	71.289	3	23.763	2.878	.050
Error	288.959	35	8.256		

Table G-3: Course-deviation Reaction Times (4 audio conditions) Tukey Test Comparisons.

(I) Audio_Scheme	(J) Audio_Scheme	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
BothCont	LateCont	-1.6292	.90862	.294	-4.0796	.8213
	DevCont	.3667	.90862	.977	-2.0838	2.8171
	BothThresh	-1.7949	.93352	.237	-4.3125	.7227
LateCont	BothCont	1.6292	.90862	.294	-.8213	4.0796
	DevCont	1.9958	.90862	.144	-.4546	4.4463
	BothThresh	-.1657	.93352	.998	-2.6834	2.3519
DevCont	BothCont	-.3667	.90862	.977	-2.8171	2.0838
	LateCont	-1.9958	.90862	.144	-4.4463	.4546
	BothThresh	-2.1616	.93352	.114	-4.6792	.3560
BothThresh	BothCont	1.7949	.93352	.237	-.7227	4.3125
	LateCont	.1657	.93352	.998	-2.3519	2.6834
	DevCont	2.1616	.93352	.114	-.3560	4.6792

G.2. Course-deviation Reaction Times (for 2 audio alerts)

Met normality and homogeneity assumptions.

Table G-4: Course-deviation Reaction Times (2 audio alerts) Within-Subjects Contrast.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	14.534	1	14.534	3.311	.077
Scenario * Audio_Scheme	Linear	1.089	1	1.089	.248	.621
Error(scenario)	Linear	162.403	37	4.389		

Table G-5: Course-deviation Reaction Times (2 audio alerts) Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	9007.397	1	9007.397	1146.991	.000
Audio_Scheme	69.684	1	69.684	8.874	.005
Error	290.564	37	7.853		

G.3. Transformed (natural log) Late-arrival Reaction Times

Met normality and homogeneity assumptions after original data was transformed with a natural log transformation.

Table G-6: Transformed (natural log) Late-arrival Reaction Times Within-Subjects Contrasts.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	6.513	1	6.513	20.737	.000
scenario * Audio_Scheme	Linear	1.619	3	.540	1.719	.181
Error(scenario)	Linear	10.992	35	.314		

Table G-7: Transformed (natural log) Late-arrival Reaction Times Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	244.837	1	244.837	305.851	.000
Audio_Scheme	8.028	3	2.676	3.343	.030
Error	28.018	35	.801		

Table G-8: Transformed (natural log) Late-arrival Reaction Times Tukey Test Comparisons.

(I) Audio_Scheme	(J) Audio_Scheme	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
BothCont	LateCont	.0092	.28293	1.000	-.7539	.7722
	DevCont	-.7099	.28293	.076	-1.4729	.0532
	BothThresh	.0633	.29069	.996	-.7206	.8473
LateCont	BothCont	-.0092	.28293	1.000	-.7722	.7539
	DevCont	-.7191	.28293	.071	-1.4821	.0440
	BothThresh	.0542	.29069	.998	-.7298	.8381
DevCont	BothCont	.7099	.28293	.076	-.0532	1.4729
	LateCont	.7191	.28293	.071	-.0440	1.4821
	BothThresh	.7732	.29069	.054	-.0107	1.5572
BothThresh	BothCont	-.0633	.29069	.996	-.8473	.7206
	LateCont	-.0542	.29069	.998	-.8381	.7298
	DevCont	-.7732	.29069	.054	-1.5572	.0107

G.4. Transformed (natural log) Late-arrival Reaction Times (with BothCont/LateCont/BothThresh Combined against DevCont)

Met normality and homogeneity assumptions after original data was transformed with a natural log transformation.

Table G-9: Transformed (natural log) Late-arrival Reaction Times (with BothCont/LateCont/BothThresh Combined against DevCont) Within-Subjects Contrasts.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	7.476	1	7.476	23.730	.000
scenario * Audio_Scheme	Linear	.954	1	.954	3.029	.090
Error(scenario)	Linear	11.657	37	.315		

Table G-10: Transformed (natural log) Late-arrival Reaction Times (with BothCont/LateCont/BothThresh Combined against DevCont) Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	228.000	1	228.000	300.624	.000
Audio_Scheme	7.984	1	7.984	10.528	.002
Error	28.062	37	.758		

G.5. NASA TLX Scores

Met normality and homogeneity assumptions.

Table G-11: NASA TLX Scores Within-Subjects Contrasts.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	3.364	1	3.364	.058	.811
Scenario * Audio_Scheme	Linear	215.197	3	71.732	1.234	.312
Error(scenario)	Linear	2035.166	35	58.148		

Table G-12: NASA TLX Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	96127.322	1	96127.322	188.194	.000
Audio_Scheme	1244.548	3	414.849	.812	.496
Error	17877.551	35	510.787		

G.6. Missed Radio Calls

Met normality and homogeneity assumptions.

Table G-13: Missed Radio Calls Within-Subjects Contrasts.

Source	Scenario	Type III Sum of Squares	Df	Mean Square	F	Sig.
Scenario	Linear	34.307	1	34.307	1.411	.243
scenario * Audio_Scheme	Linear	65.774	3	21.925	.902	.450
Error(scenario)	Linear	850.944	35	24.313		

Table G-14: Missed Radio Calls Between-Subjects Effects.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	7966.465	1	7966.465	92.043	.000
Audio_Scheme	210.033	3	70.011	.809	.498
Error	3029.300	35	86.551		

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